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A NEW APPROACH FOR ACSR SELECTION AND INSTALLATION - FOR OVERHEAD TRANSMISSION LINES

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled A NEW APPROACH FOR ACSR SELECTION AND INSTALLATION - FOR OVERHEAD TRANSMISSION LINES submitted by AKHTAR M. ANSARI in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

ABSTRACT

This thesis can be broadly divided into two parts.

In the first part, the choice of conductor size to meet the load current demand is approached from a probabilistic method which establishes the magnitude of the overload risk.

In the second part the problem of conductor installation and sagging has been approached in a new way which improves upon and corrects the commonly used procedures. A detailed discription of the method and a computer program for determination of sag tables is included.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

CHAPTER 1

THE PROJECT

1-1 Introduction:

The cost of a transmission line is dependent on many factors including the size of conductor selected and the tension at which it is installed. The importance of the proper choice of conductor size can hardly be overemphasized since it has a direct effect on capital costs. The second factor, the stringing tension, also has a substantial effect on the line costs, as is graphically shown in figure-1.

The objective of this project is to provide a method for the optimisation of transmission line costs with respect to the above-indicated factors.

In this report the present day practices for both the above factors are reviewed and new approaches developed. A probalilistic method is proposed for conductor size evaluation taking into account the effects of time variations of load currents and daily temperatures to establish a risk of overload in a manner similar to that used for loss of load calculations (1). In the second part a new and comprehensive method is developed for the determination of data for conductor installation. A computer algorithm is developed for implementation of the method.

1-2 Selection of Conductor Size:

As indicated earlier, the cost of a transmission line is directly influenced by the conductor size. A conductor

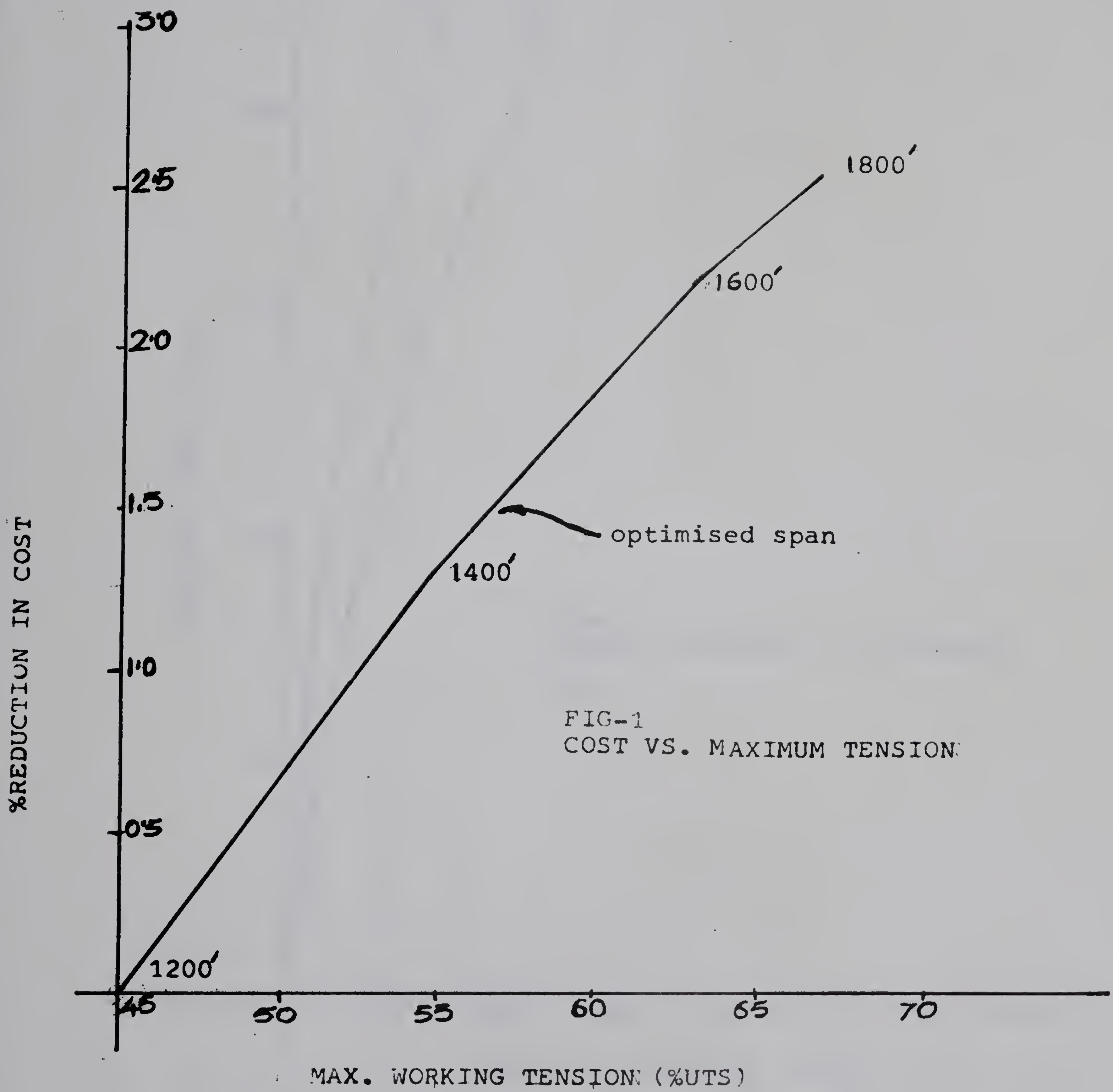


FIG-1
COST VS. MAXIMUM TENSION

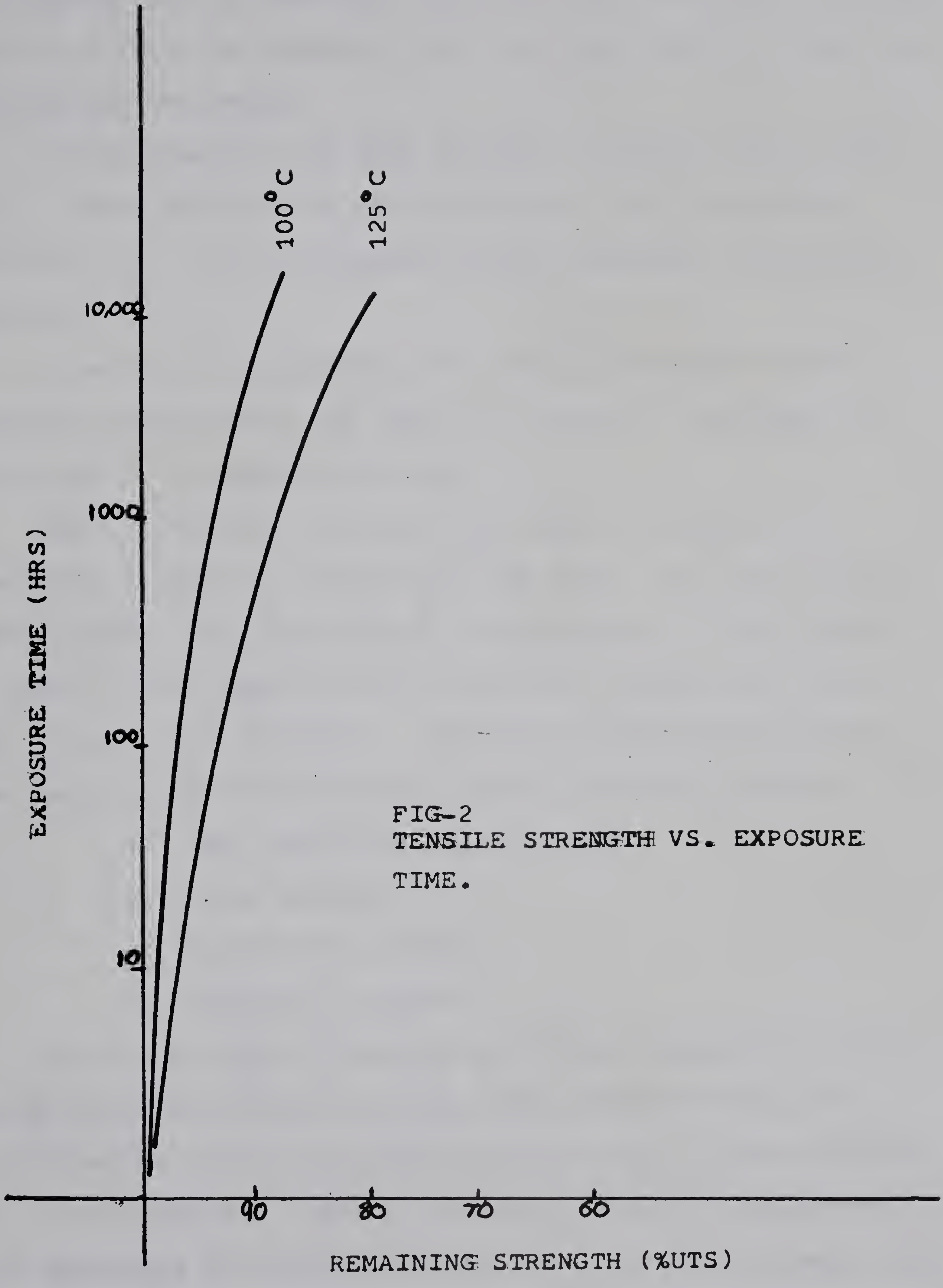


FIG-2
TENSILE STRENGTH VS. EXPOSURE TIME.

over-design (as is presently done) not only results in a larger and more expensive conductor but also makes heavier towers and foundations necessary.

Conventionally, for this purpose, ampacity tables are used. These tables list current-values based on thermal criteria (2). Such an approach gives extremely conservative results.

At elevated temperatures the tensile strength of the conductor deterioates (as shown in figure-2), resulting in increases in elongation and sag.

The reduction of strength over the lifetime of the conductor depends on temperature and time. If, for example, three percent loss in strength is allowable, a total period of about 10,000 hours (Table01) at 100^{o}C during the life of the conductor is tolerable. Conductor temperature, during its usage, would be determined by the following factors

a) Heat radiation from conductor

b) Solar heating

c) Convection cooling

d) Conductor current

Setting an upper limit for conductor temperature (with annealing as a factor) and taking the above factors into consideration current carrying capacity for a given conductor can be dertermined. Several different empirical equations have been developed for these calculations. Figure-3 compares some of these methods indicating fairly large differences. These differences are mainly due to differences in assumptions as to ambient temperature, maximum temperature, solar heating, etc.

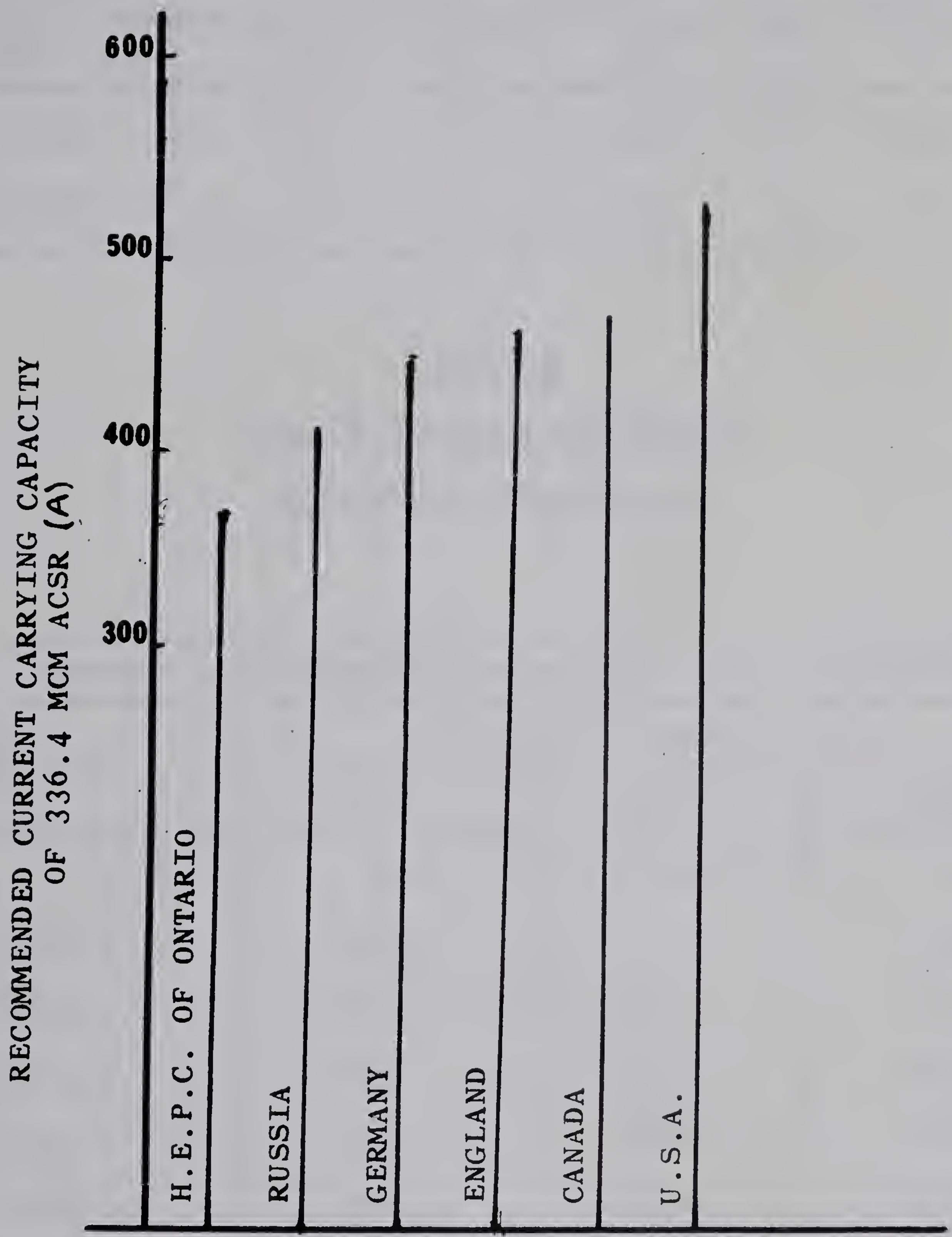


FIG-3 EXAMPLE OF RECOMMENDED AMPACITY IN VARIOUS COUNTRIES(12)

Total heating period	Calculated loss of strength with a steel/aluminum ratio of 0.13 at		
	85°C	100°C	125°C
Hrs	%	%	%
1,000	1.0	2.0	3.4
10,000	1.4	3.0	4.7

TABLE-1

LOSS OF TENSILE STRENGTH IN

ACSR DUR TO HEATING (3)

Thermal load capacity at various cond. temperatures			
Line Voltage KV	Load per circuit (MW)		
	50°C	80°C	125°C
132 A.C.	89	140	183
275 A.C.	596	965	1282
400 A.C.	1735	2807	3730
750 A.C.	4531	7554	10153
250 D.C.	872	1454	1954
350 D.C.	7566	13092	17790

TABLE-2

EFFECT OF CONDUCTOR TEMPERATURE ON

THERMAL LOAD CAPACITY (MAIN

PARAMETERS: AMBIENT TEMP - 20°C & CROSSWIND= 44·7 cm/s)(3)

House and Tuttle (13) have developed what appears to be the most comprehensive approach in use at present. This includes latitude and line direction effects. Fairly accurate (error=±4%) results can be obtained from the following expression (12). This expression alongwith its simplified form has been chosen for discussion for simplicity's sake.

$$I^2R+AS'D=13.8\times10^{-4}(VD)^{.5}\theta$$
$$+\pi DES\left[(\theta+T+273)^4-(T+273)^4\right] \text{------------}(1)$$

Where

I=Current in amperes

A=Solar absorption coefficient,

S=Intensity of Solar radiation, watts per square centimeter

D=Conductor diameter in centimeters

V=Wind velocity in centimeters per second

R=Resistance of conductor per centimeter in ohms.

θ=Temperature rise of conductor in ^oC

E=Emissivity of conductor

$S=5.7\times10^{-12}$

T=Ambient temperature in ^oC

This expression can be simplified (12) to the following form:

$$I^2=3300(3V^{0.5}D^{2.5}+D^3)\theta-.166\times10^6D^3 \text{----------}(2)$$

Where V, D and θ are given in mph, inches and Fahrenheit respectively.

The results obtained with these expressions are conservative in that the current limits used are based on worst conditions. In fact, high loads and high ambient temperatures do not necessarily coincide.

In the United Kingdom the practice is to assume a maximum operating temperature of $50^{\circ}C$ (4). This is the temperature set by regulations for the maintenance of statutory ground clearances. This implies that a conductor should have more than one ampacity value i.e. separate for winter and summer. For instance, 54/7/0.125 in. 'Zebra', would be rated 650 Amps in summer and 800 amps in winter.

The need for correctly choosing the maximum operating temperature is more readily understood if figure-4 is referred to. This figure indicates the dramatic increase in the ampacity for a small increase in operating temperature. In the United Kingdom it has been suggested (4) that the maximum continuous operating temperature should be set at $75^{\circ}C$ - this would permit an increase in ratings by 33% - 100%.

A paper (3) published by IEE presented an exhaustive study regarding the effect of conductor temperature on thermal loading capacity. Table-2 gives an abstract of the relevant results indicating the importance of correctly and appropriately choosing the maximum operating temperature.

In addition to selection of the maximum operating temperature it is necessary to select suitable values for other variables which affect the ampacity of overhead conductors. Of these the ambient temperature, wind velocity and insolation are most important. Chapter-2 proposes a probabilistic

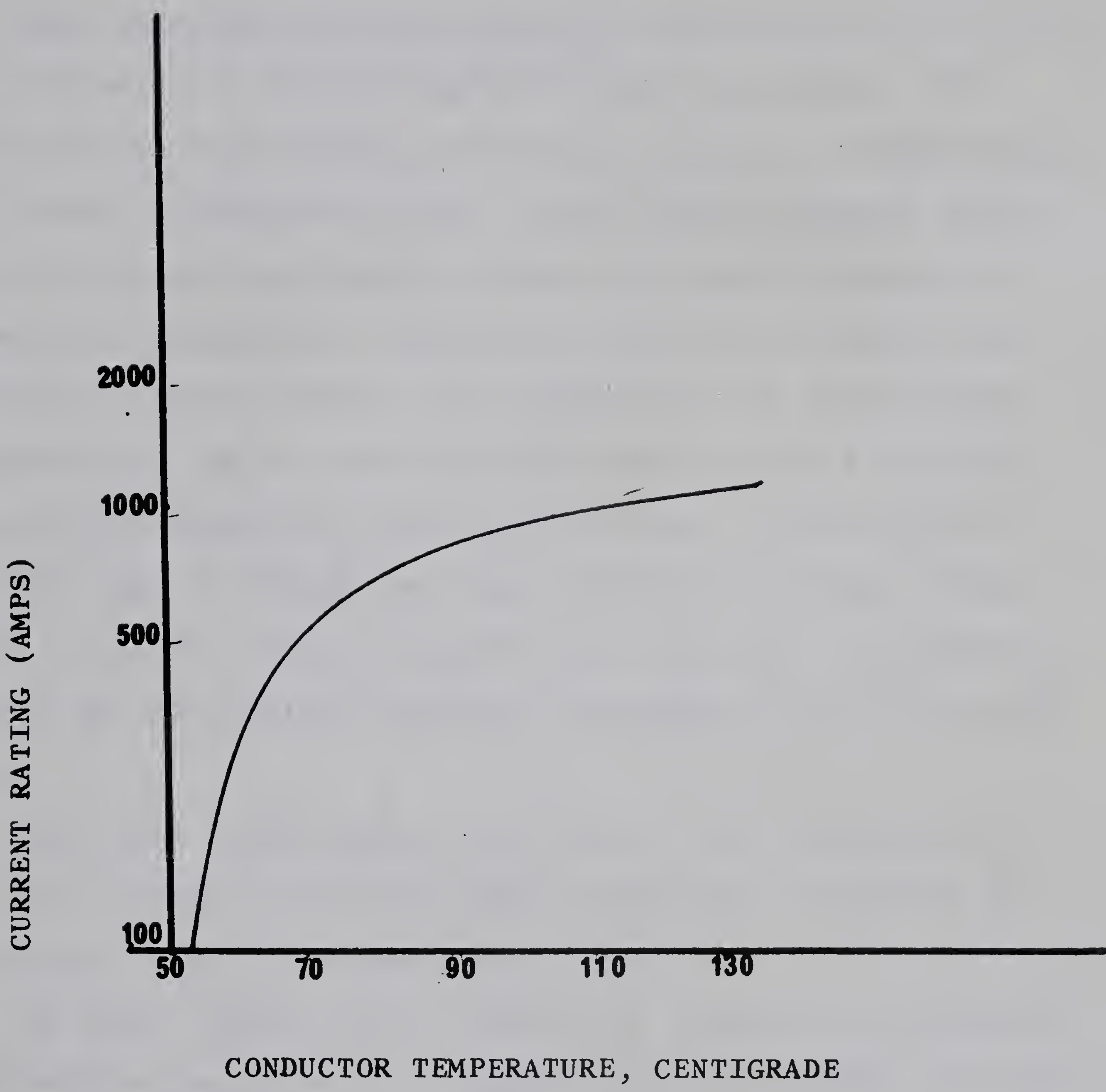


FIG-4 CURRENT RATING VS. COND. TEMPERAYURE
(0.4 sq. in. cu. equt) (3)

approach to this problem.

1-3 Calculation of Installation Data:

The conductor-stringing phase of construction of an overhead transmission line is one of the most important. The conductor has to be strung carefully on towers so that statuetory ground clearances are met. This implies sagging of the conductor by such an amount so that the ground clearance is correct, at a specified temperature after the conductor has undergone initial bedding down, strains due to self-weight, permanent-set due to cyclical worst conditions and metallic creep over a specified long period of time. Thus before a conductor can be strung one needs installation data, giving initial sags for various temperatures and spans calculated to satisfy the prescribed conditions throughout the life of the line.

For about fifty years, many methods and concepts have been put forward by various people regarding calculation of stringing - data for transmission lines (6).

An ideal design can be obtained if a method is available to determine the state of a transmission line during its lifetime. Such a method, to provide best results, would need the influencing factors (such as meteorological data and physical properties of conductor-material) in their most accurate form.

In Chapter-3 a new method is proposed which represents the behaviour of the conductor much more accurately. The increased accuracy implies an increase in confidence in the

end-results, with a consequent reduction in costs (since the factor of safety may be reduced in choosing of operating conditions e.g. maximum allowable tension).

Historical Background

As stated earlier, the new method which is being presented in this report, is preceeded by many less comprehensive concepts. The most important of them are listed below with a few short comments.

I. Classical Method:

This is an analytical method and is outlined in detail in John McCombe's book (14) "Overhead Line Practice".

The theory of calcultions by this method is based on the recognition of the nature of the curve formed by a suspended conductor i.e. a catenary. Since the relations of a catenary are somewhat complicated the curve is approximated by a parabola.

In this method the conductor stress for one set of conditions (temperature and conductor loading) is specified then the stress for other conditions is calculated. The basic formula is given below. In the formula the quantities referring to the basic conditions are indicated by subscript '0' while subscript '1' indicates quantities for the new set of conditions for which the calculations are made.

$$f_1^{\,2}\left[f_1-(K-AEt)\right]=\frac{l^2D^2q_1^{\,2}E}{24}$$

$$S=\frac{l^2D^2q_1}{8f_1}$$

Where

$$K = f_o - \frac{l^2 D^2 q_o^2 E}{24 f_o^2}$$

f= stress in psi

A= Coeff. of linear expansion per ^{o}F

t= $t_1 - t_o$ (^{o}F)

E= Modulus of elasticity in psi

l= Span in feet

D= Weight of cond. per ft. per $in.^2$ (lb)

S= sag in feet.

The main short coming of this method is that the concept of initial or final sags or tensions cannot be incorporated in this because:

A. For evaluation of initial sags the initial modulus of of elasticity would have to be determined, which is not possible since this quantity is non-linear by nature and varies over a wide range depending upon the applied stress.

B. Final sags and tensions cannot be determined by this method since there is no provision for determination of elongation of conductor due to creep (this is longitudinal deformation which a tensioned conductor experiences with the passage of time).

In addition to the above there would be errors arising due to the assumption of the catenaries as parabolas.

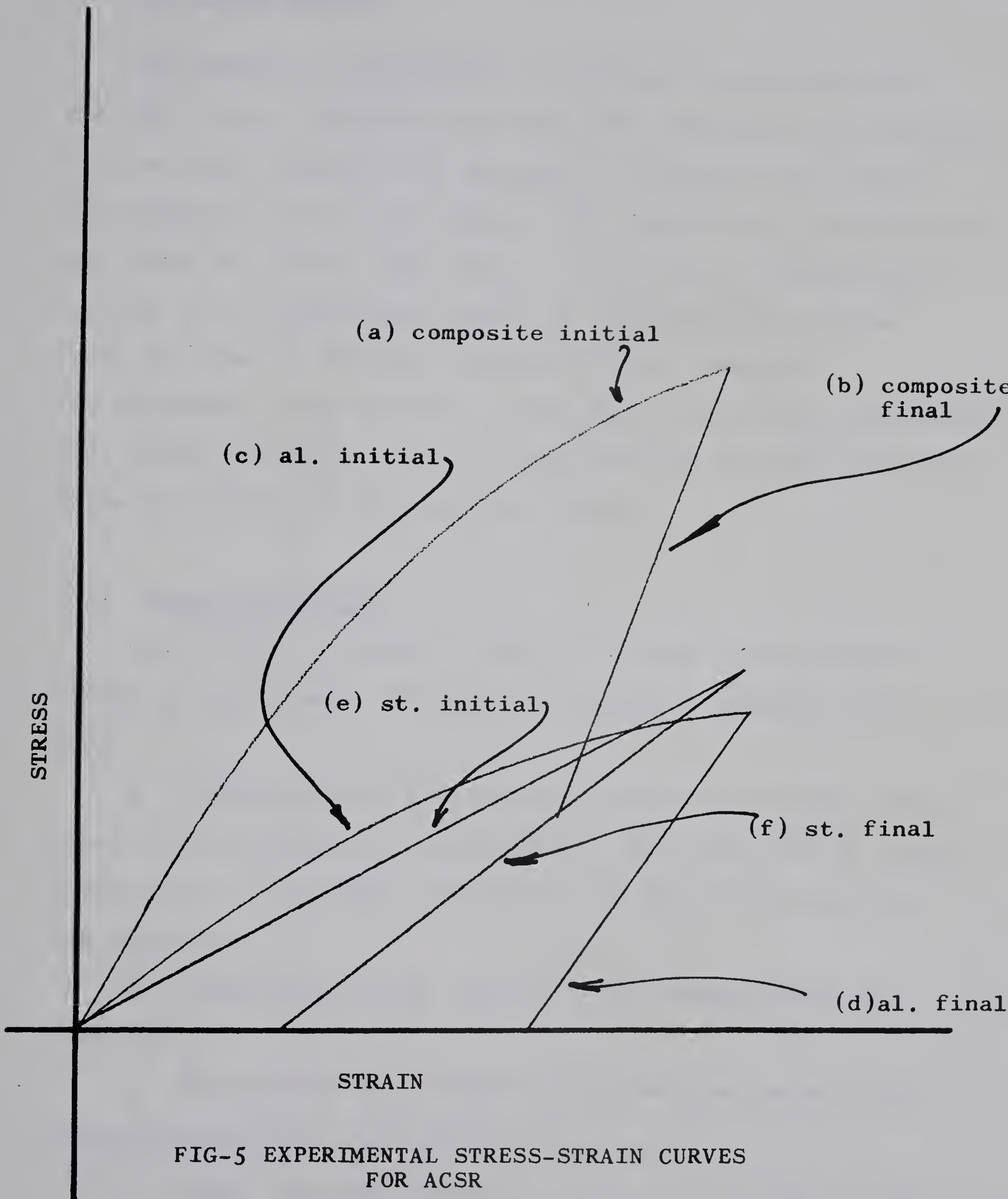


FIG-5 EXPERIMENTAL STRESS-STRAIN CURVES FOR ACSR

II. Unit Span Method:

This method, conceptually, is the same as the previous one, but is in a tabulated form and uses relations corresponding to a catenary instead of a parabola. Initially this method was suggested by Percy H. Thomas (6). Sag-tension calculations are based on span of unit length. This type of manipulation results in a considerable saving of involved calculations. Later on James S. Martin (Copperweld Steel Company) (6) prepared a very elaborate tabulation of unit-span dimensions. This method is quite simple to apply but has the same disadvantages as listed for the previous method.

III. Graphical Method:

This method is based on study of actual stress-strain curves of conductors. It involves extensive drawing board work.

A. Preparation of stress-strain curves and creep curves based on data obtained by experiments. The basic set of curves correspond to the actual temperature at which the experiment was conducted.

B. Conversion of the above to other temperatures of interest.

C. Preparation of preliminary sag-tension curves from catenary tables for the desired ruling spans.

D. Super-position of stress-strain curves for various temperatures on the sag-tension curves.

Procedural details and basic conductor data are given in a booklet published by ALCOA (5).

This method gives good results since it treats the strung conductor as a catenary and is based on the actual stress-strain behaviour of the conductor.

Inaccuracies arise in the concept employed to manipulate the basic stress-strain data, obtained at some temperature, to construct stress-strain curves for other temperatures. To clarify, suppose the stress-strain curves obtained for some ACSR at a test temperature of, say, 70°F are as shown in figure-5.

Curves labelled a, c & e in the figure give 'initial' curves for the composite conductor, aluminum only, and steel only respectively. The term 'initial' indicates the relationship obtained when the conductor is loaded for the first time. Similarly, curves b, d & f correspond 'final' relationship (i.e. pertaining to that part of experiment when the conductor was being unloaded) for composite, aluminum only and steel only respectively.

In the graphical method, when stress-strain curves for other temperatures are needed the individualcurves for aluminum and steel are shifted according to their respective thermal coefficients and then added to obtain the curve for the composite conductor. For instance, suppose curves for 0°F are needed. Contractions in aluminum and steel corresponding to a decrease of 70°F in temperature are computed and curves shifted as shown in figure-6. Addition of shifted curves gives curves a' and b', the composite curve for a temperature of 0°F. Similarly curves for other temperatures of interest are constructed.

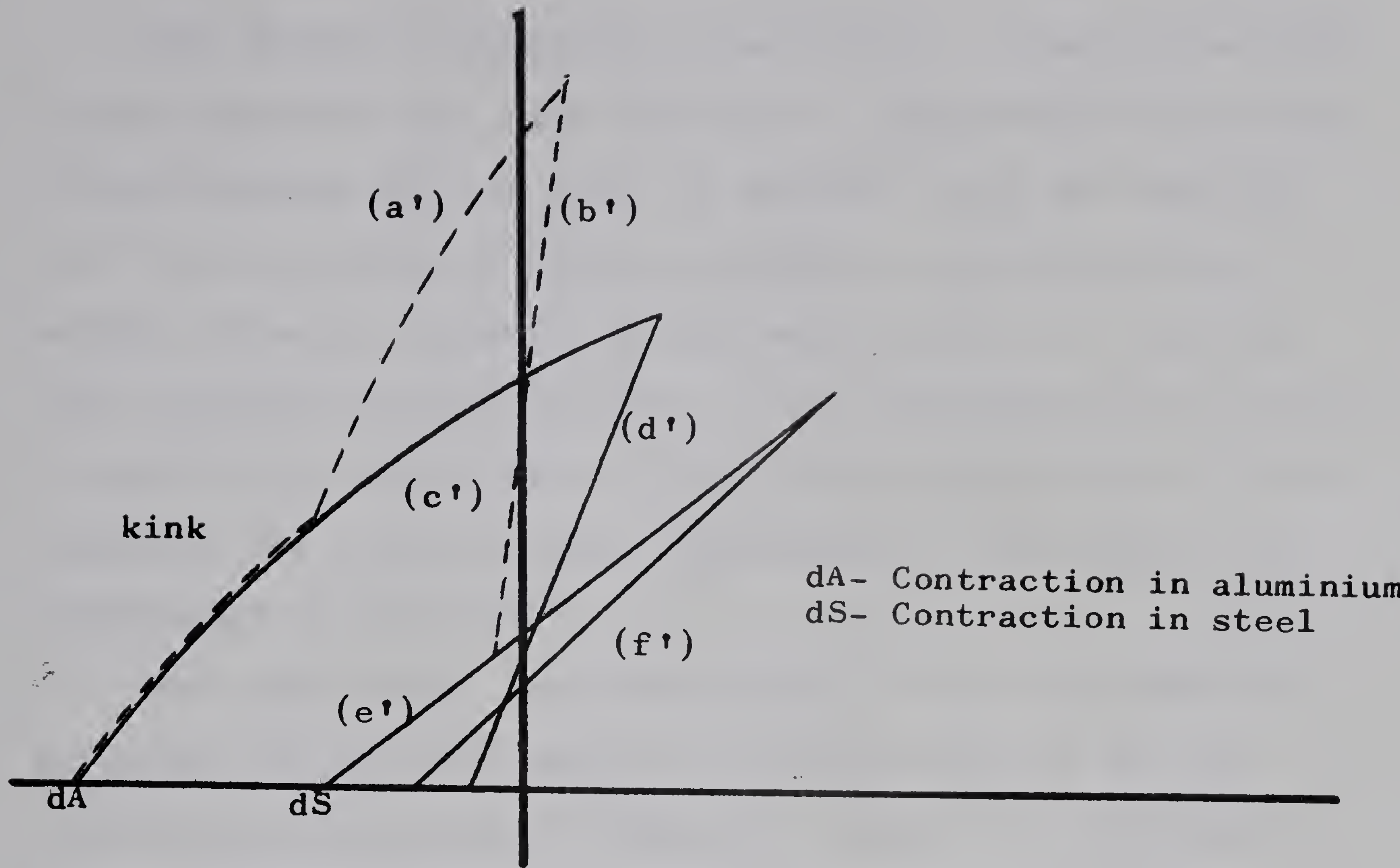


FIG-6 CURVES FOR $0^{o}F$ (ALCOA)

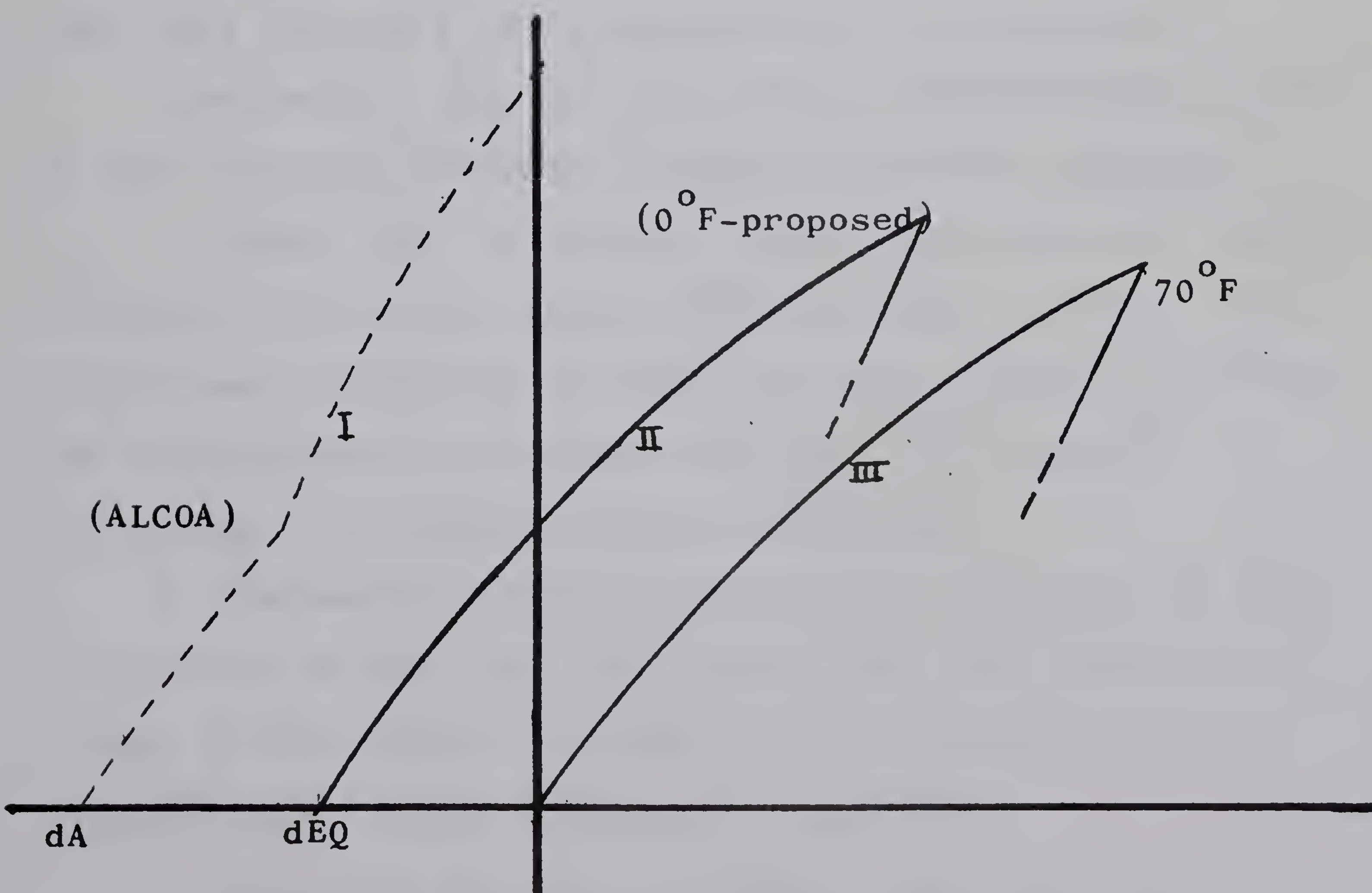


FIG-7 CURVES FOR $0^{o}F$ PROPOSED)

This method of obtaining stress-strain curves for various temperatures does not seem realistic. Independent contraction of the aluminum and the steel is implied. This is unlikely due to the presence of intense friction, especially since several miles of conductor is generally involved. Secondly, this approach produces a 'kink' in the composite curve (figure-6) which would not be there if the stress-strain curve of the conductor was expreimentally, determined at $0^{o}F$ rather than constructed as described.

More reasonably, the stress-strain curves for ACSR for different temperatures would be as represented by the two solid-line curves shown in figure-7. Curve II is identical to curve III but shifted by an amount determined by the equivalent modulus of elasticity (6). The slope of curve II is less than that of I but the variation is negligible.

Experimental data and fabrication specifications found in the following references support the above arguments.

A. Metal Data (7) gives a table which shows the effect of temperature on the modulus of elasticity of steel. The table shows a decrease to $29x10^{6}$ psi from $29.5x10^{6}$ psi when the test temperature is increased from $70^{o}F$ to $100^{o}F$ indicating a negligible change in rigidity.

B. Mechanical Properties of Metals (8) refers to this in figure-3 on page 56. The figure shows that there is no change in the modulus of elasticity of aluminum when the temperature is varied between $0^{o}C$ and $200^{o}C$.

C. ASTM (9) and BSS (10) specify that the successive layers of a stranded conductor shall have opposite directions

of lay. This indicates that as soon as some external tension is exerted the inter-layer friction would develop making relative movement of aluminum and steel impossible.

In the end it may be concluded that the basic assumption in the graphical method is faulty and does not help yield correct results. Secondly the temperature listed on the stress-strain charts (The Aluminum Association and ALCOA always list a temperature on their charts which is actively used in developing curves for other temperatures) has no relevance other than recording the temperature at which the data was obtained.

In chapter-3 a new method is proposed which is based on the study of an ACSR as a whole and employs as few assumptions as possible.

CHAPTER-2

A STATISTICAL TECHNIQUE FOR SELECTION OF OVERHEAD CONDUCTOR

This chapter gives an outline for a statistical method for the selection of the most suitable size of conductor.

In general the current carrying capacity of a given conductor depends on the available convective cooling due to wind and heat loss due to radiation caused by the difference in maximum conductor temperature and the ambient. According to the prevalent design practices the capacity would correspond to the maximum expected ambient temperature and the lowest wind (general value taken varies between 0 and 2 mph). This approach has at least one point to its credit i.e. theoretically it removes all chances of the conductor being over loaded. On the other hand, it provides an unneccessarily expensive design, as it is very unlikely that the ambient temperature would be the maximum expected alongwith the wind at its lowest when the load current is at its peak.

In a design problem like this, when the variables are of stochastic nature, the most suitable technique would have to be predominantly statistical. The following paragraphs outline such a method.

This concept is based on comparative study of various sizes of conductor and determining the over-load risk-factor associated with each size and finally choosing the conductor for which the calculated risk is equal to or just under a pre-determined design-risk.

If the probability of load current equal to or greater than I is given by P $(I_L \geqslant I)$ and the probability of a given conductor having a current-carrying capacity equal to I is given by P $(I_{cap}=I)$ then the probability for insufficient capacity would be given by

$$\sum P(I_L \geqslant I) \cdot P(I_{cap}=I) \quad \ldots\ldots (3)$$

This expression is a measure of the risk and provides a very convenient way to undertake a comparative study of overhead conductors.

Example:

A. PRELIMINARY CONDITIONS AND DATA:

1. Expected life of conductor - 20 years
2. Max. operating temperature - 80°C
3. Max. allowable overload temp. - 125°C
4. Allowable loss in strength over lifetime - 5% of UTS
5. Profile of expected load current - as given in fig-8
6. Profile of expected ambient temperature - as given in fig-9
7. Wind velocity - suitable wind velocity has to be chosen. For this example 1 mph is taken

B. EVALUATION OF RISK FACTOR

Conductors being considered for this example

1. DRAKE, 795 MCM, 1.108 in. dia.
2. ORTOLAN, 1033.5 MCM, 1.213 in. dia.
3. BITTERN, 1272 MCM, 1.345 in. dia.

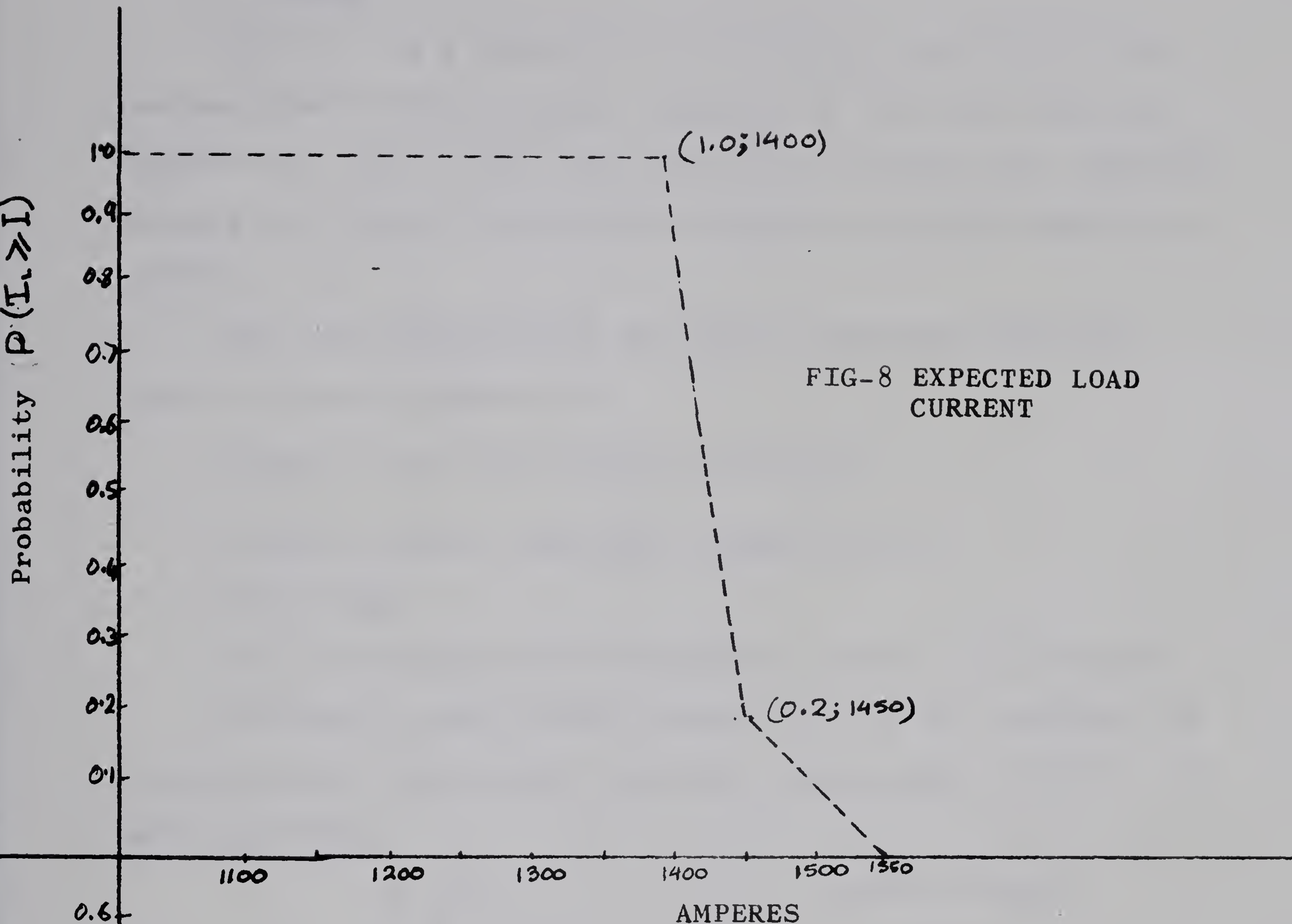


FIG-8 EXPECTED LOAD CURRENT

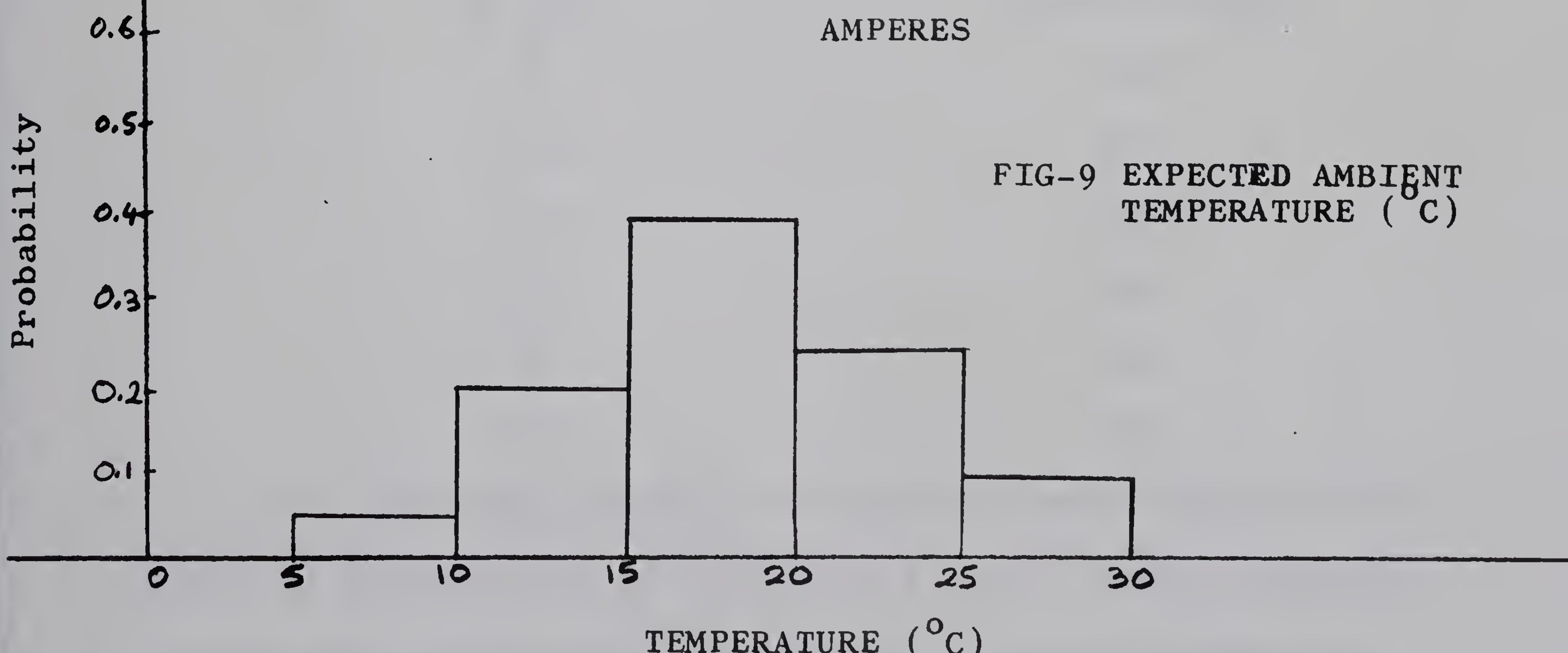


FIG-9 EXPECTED AMBIENT TEMPERATURE (^{o}C)

1. DRAKE

First of all a check has to be made to see whether the maximum load current (1550A) occurring at the worst ambient temperature (30^oC) and 1 mph wind would increase the conductor temperature beyond the maximum allowable overload temperature (125^oC).

Thus, for $\theta=125-30=95$, the current carrying capacity would be (using equation-2):

$$I^2=3300\ (3.0V^{0.5}D^{2.5}+D^3)\theta-0.166x10^6D^3$$

$$I^2=3300\ (3.876+1.362)95x\tfrac{9}{5}-0.166x10^6x1.362$$

$I=1651$ Amps.

This is in excess of the maximum expected load current.

Similarly, load carrying capability for the conductor is calculated for the maximum operating temperature of 80^oC - as tabulated below

θ (^oC)	Current (Amps)
50	1152
55	1218
60	1280
65	1340
70	1397
75	1451

With the above figures the ambient--temperature profile given in figure-9 can be transformed into a current-capacity profile and superimposed on figure-8 as show in figure-10a.

From figure-10a the expression $\Sigma P(I_L > I).\ P(I_{cap}=I)$ can be evaluated as:

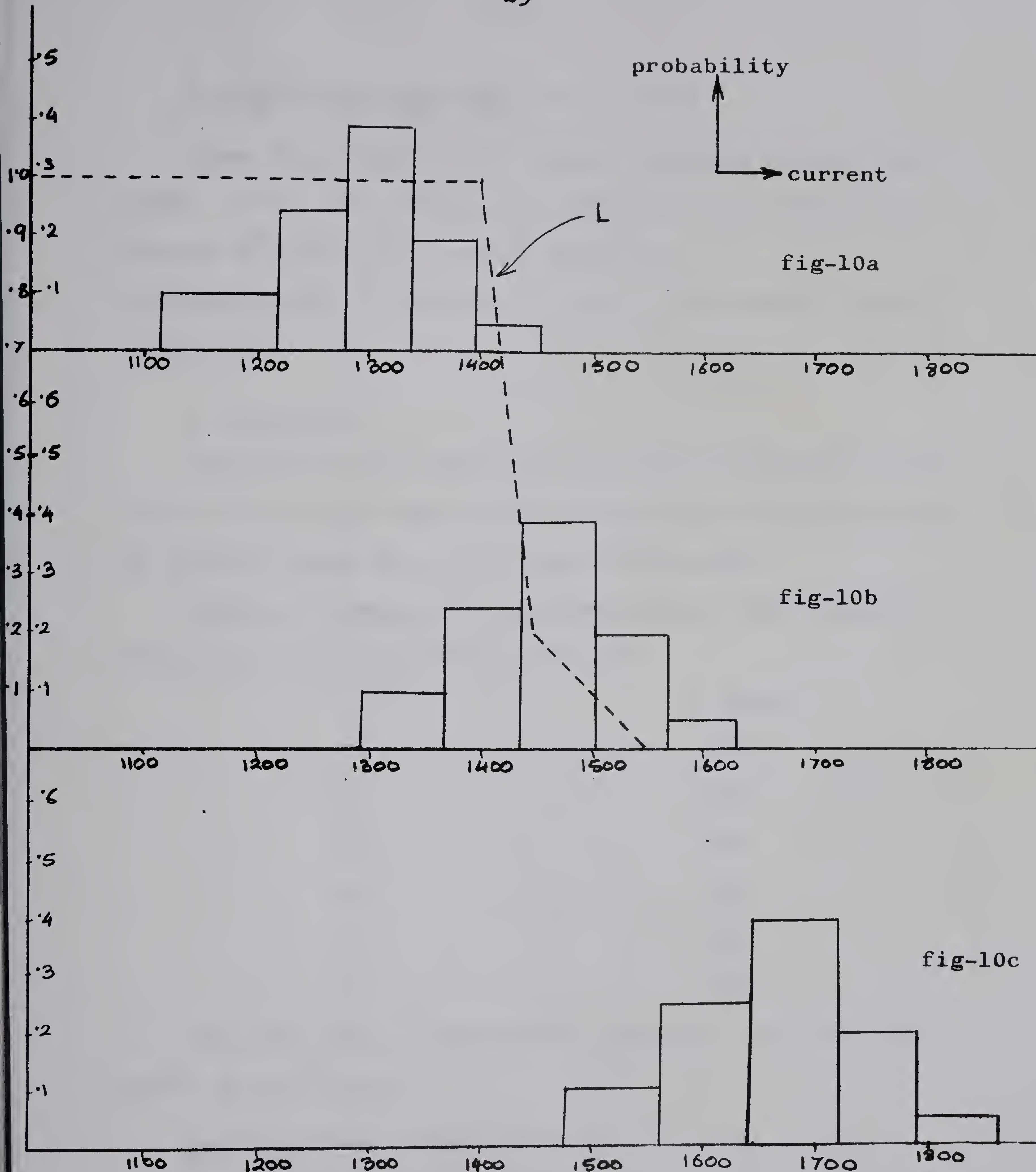


FIG-10

Note: Expected-load-curve 'L' is shown superimposed on fig-10b. Similar superimpositions on 10a &10b would be needed. Scale for 'L' is on left.

$$\frac{1}{10}x1+\frac{2.5}{10}x1+\frac{4}{10}x1+\frac{2}{10}x1+\frac{.5}{10}x0.57 = 0.9785$$

Since this risk is for 6 hours every day during summer months. Hence for twenty years the overload (temperature between $80^{\circ}C$ and $125^{\circ}C$) would exist for

0.9785x6x20x30x6 = 21136 hrs. (on a 30 day/month, 6 month risk period)

2. **ORTOLAN**:

Since Drake was sufficient for worst conditions there is no need to make worst condition calculations for ortolan and Bittern since these are larger conductors.

Similar to Drake, for capacity-profile the following results are calculated and tabulated:

θ ($^{\circ}C$)	I (Amps)
50	1295
55	1369
60	1440
65	1506
70	1570
75	1630

With the above, figure 10-b is obtained, and the risk-factor is calculated:

$$\frac{1}{10}x1+\frac{2.5}{10}x1+\frac{4}{10}x0.07+\frac{2}{10}x.01=0.38$$

This would give over-load hours

=.38x6x30x6x20

=8208 hrs.

3. BITTERN

θ (^{o}C)	I (Amps)
50	1479
55	1565
60	1645
65	1722
70	1796
75	1866

Using the above figure-10c can be plotted and the risk factor is

$\frac{1}{10}$x.025=.0025

And the overload-hours

=.0025x6x30x6x20

=54

Referring the table-1 the best choice under these hypothetical conditions would be 'Ortolan' since with 8208 overload-hours the loss in strength would be close to 4.5% of UTS over the life of the conductor. On the other hand the loss in strength in Drake would be more than 5% of UTS (the specified limit) and Bittern would be under-utilised with the loss in strength of only about 1% of the UTS.

CHAPTER 3

THE NEW APPROACH FOR CONDUCTOR INSTALLATION-DATA CALCULATIONS

3-1 Introduction

Physical behaviour of a suspended cable can be adequately studied if the following two parameters are known throughout the life-time of the conductor.

A. Stress and strain at any given time.

B. The shape of the catenary formed.

The above two factors are not inter-dependent. For example when the stress increases it can change the existing catenary to either one with a larger sag or one with a lesser sag depending upon the reason which caused the increase in stress i.e. the effect of a decrease in the ambient temperature would be opposite to that of the conductor getting some ice load, while both of these conditions would cause an increase in stress.

The basis of the new method is the close tracking of two conductor state-points (one giving the stress-strain condition and the other the shape of catenary). The state-points are followed as the ambient conditions change and time passes. No assumptions are made barring one to which there is no alternative viz. the worst conditions are assumed to occur after six months of conductor installation. The basis for this assumption is the fact that in general, conductor stringing is done in summer and the worst conditions occur in winter (low temperature and ice). However, this can be easily

modified if there is data available indicating that the worst conditions would occur at some time other than six months.

3-2 <u>Preliminary Preparations:</u>

Initially governing conditions must be established. For comparison design criteria preferred by ALCOA (5) are used.

A. Initial tension at $0^{o}F$ should not exceed 33⅓% of the ultimate tensile strength (UTS) of conductor.

B. Loaded tension at $0^{o}F$ should not exceed 40% of the UTS.

C. Final tension at $0^{o}F$ should not exceed 25% of the UTS.

In these conditions the loaded tension is considered to be 'HEAVY' (cable plus 1/2-in ice with simultaneous 4 lb/sq. ft wind acting at 90^{o} to the projected area. To the resultant 0.31 lb/ft is added), as defined by National Electric Safety Code (N.E.S.C.) of USA (11).

Since state-points are to be followed in a continuous pattern the following graphical representations are needed alongwith their equations for computerisation.

I. Curve-A (figure-11) giving the stress-strain relationship of a conductor when it is initially put under stress for the first time.

II. Curve-B, which is same as curve-A, but corresponds to reduction of load.

III. Curve-C gives conductor creep for six months i.e. longitudinal strain resulting with passage of time.

IV. Curve-D is same as curve-C but refers to a period

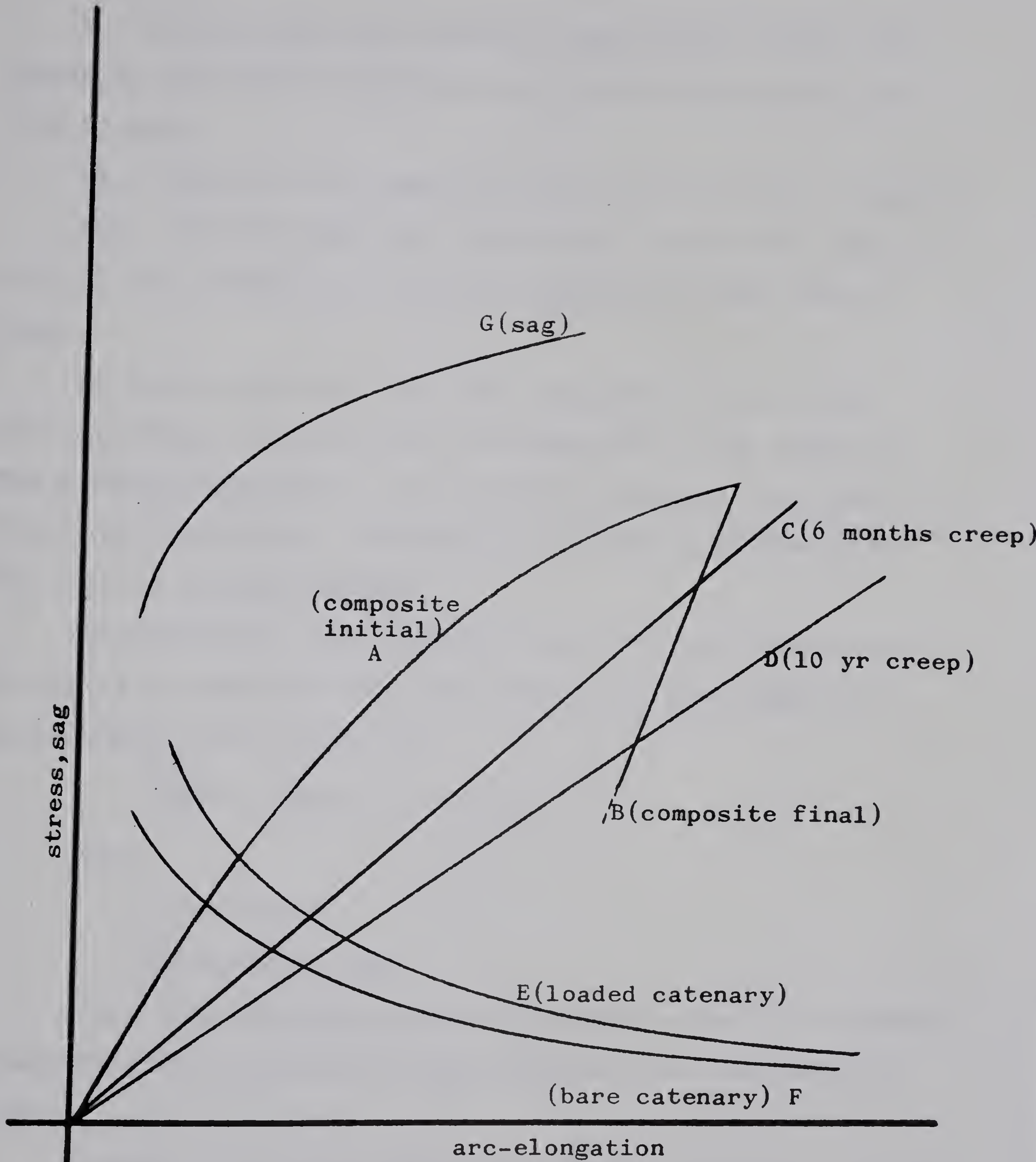


FIG-11 LABELLED CURVES

of 10 years.

V. Curve-E gives the catenary relationship between the stress in the loaded conductor to the arc-elongation in per cent of span.

VI. Curve-F is the same as curve-E but for bare conductor.

VII. Curve-G gives the relationship between the sag (or dip) of the catenary and the arc-elongation in per cent of span.

It may be mentioned here that the curves A, B, C & D are available, for just about all conductors, from ALCOA or The Aluminum Association, N.Y., both in graphical form and in the form of equations. Curves E, F & G may be plotted with the help of catenary tables.

Conventionally, the horizontal axis for all these curves is graded in terms of 'per cent increase of arc-length over span-length' and is given by

$$\frac{(L-S)}{S} \times 100 \text{------------} (4)$$

where

L=arc length

S=horizontal span.

Since this approach depends to a great extent on a detailed analysis of the 'movement' of state-points, it is considered in detail.

Consider a suspended conductor forming a catenary. Assume that the state-points are given by 0 and 0' in figure-12. Intercepts 'M' and 'N' have slightly different meanings depending on the curve to which they are applied (i.e. 'A' or

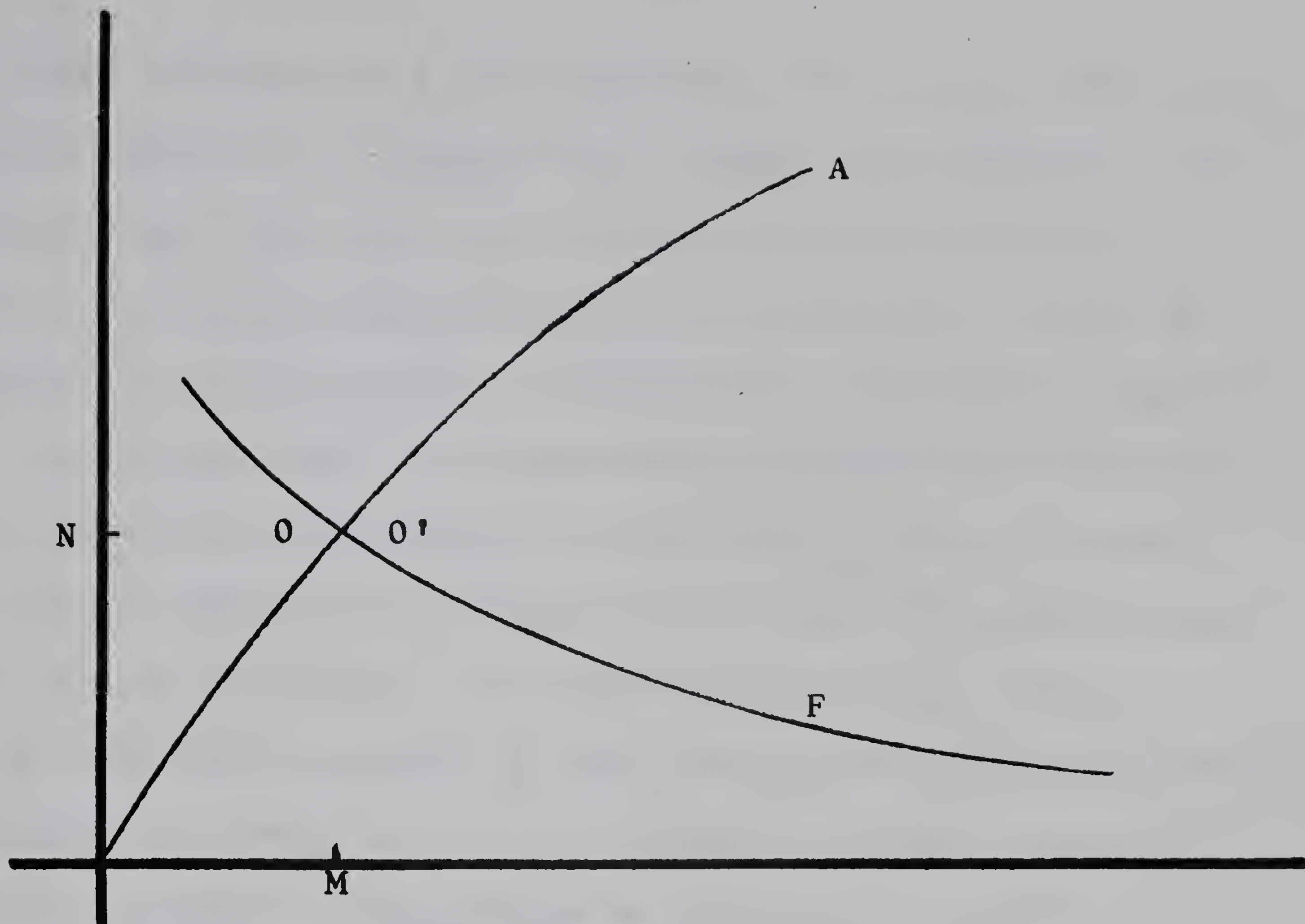


FIG-12

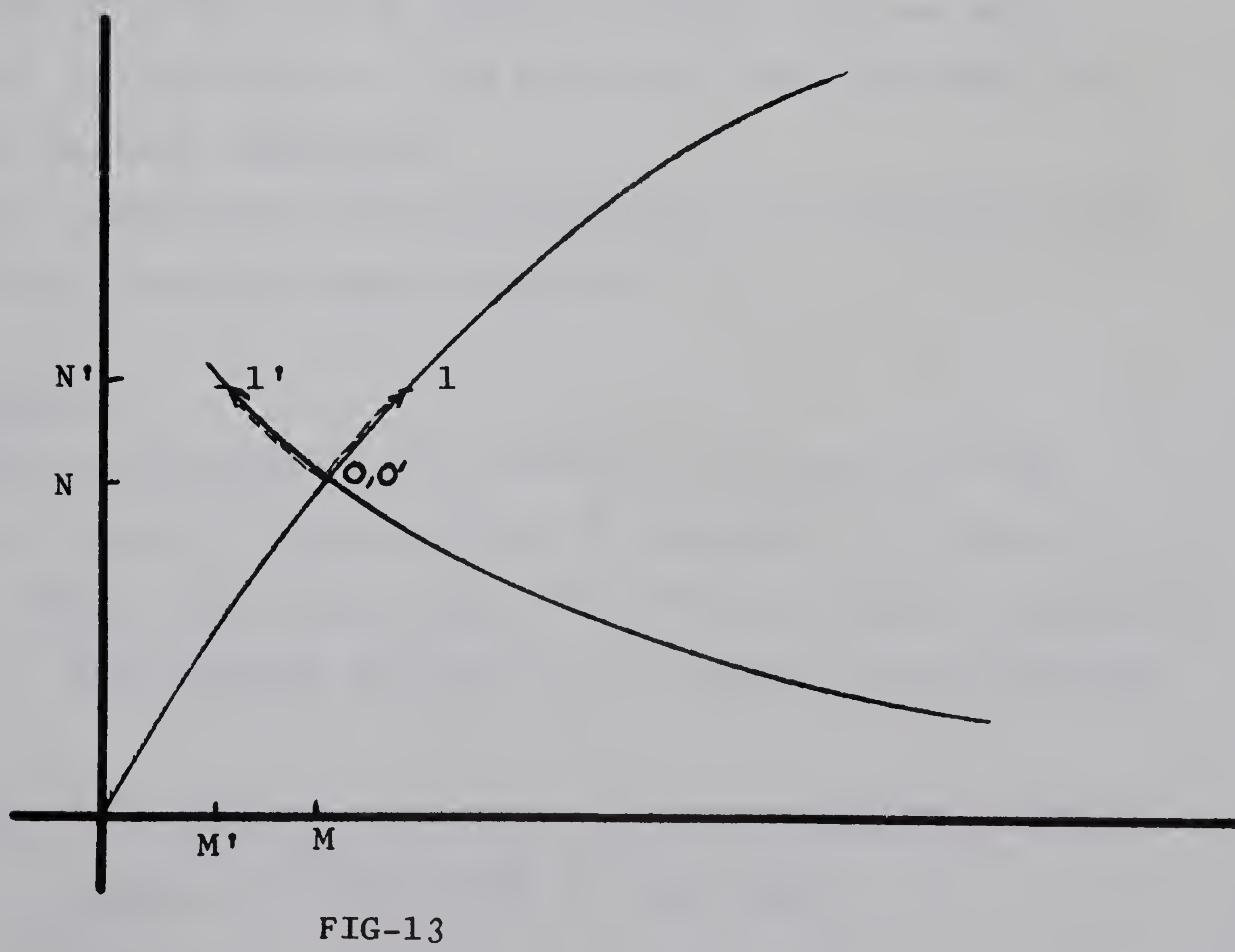


FIG-13

'F'). With reference to A, 'M' indicates the strain which would result if stress 'N' is applied to a brand new conductor. On the other hand, with reference to F, the intercept 'N' indicates the stress which would be in a catenary, formed by the conductor if its 'slack' corresponds to the arc elongation 'M'. Now suppose that the temperature decreases and the conductor contracts resulting in a reduction in arc-elongation to M' and an increase in stress to N'. The state-points would move from 0,0' to 1 and 1' as shown in figure-13. There would be a similar movement in the state-points whenever there is a change in stress due to any reason (external loading of conductor, change in temperature or conductor creep.)

3-3 The Procedure

The procedure can be broadly divided into two parts.

A. Determination of the governing condition from the set of limiting conditions.

B. Determining the stringing-data with reference to the governing-condition found in part-A.

PART-A

This part analyses the conductor as it goes through various states of tension states for a period of first 10 years (after the first 10 years the rate of creep is negligibly small). The analysis is done in five steps in the following order.

I. Stringing the conductor with the specified initial tension ($33^{1/3}$% of UTS in this case)

II. Letting the conductor undergo a creep for six months.

III. Loading the conductor with the worst loads and determing the tension under this condition. If tension is more than 40% of UTS then going back to step-I and starting with a lower value. Repeating these steps until the loaded tension turns out to be 40% of UTS or slightly less.

IV. Unloading the conductor to determine the state-point after the worst conditions are over.

V. Letting the conductor undergo a creep for $9\frac{1}{2}$ years and determining the state-point. In case the tension turns out to be more than 25% of UTS the whole, procedure has to be repeated with a smaller value at step-I until the 3^{rd} limiting condition is satisfied (i.e. the final tension not to exceed 25% of UTS)

These five steps determine the governing condition (i.e. the most critical of the three). For example, suppose the final result is that if the step I is started with a tension 23.5% of UTS the loaded tension works out to be 39.9% of UTS and the final tension is found equal to 14% of UTS. This indicates that the governing condition is the loaded tension, implying that for a given span if the loaded tension is less than 40% of UTS then the other conditions are automatically satisfied.

This general description of Part-A can be elaborated with diagrams.

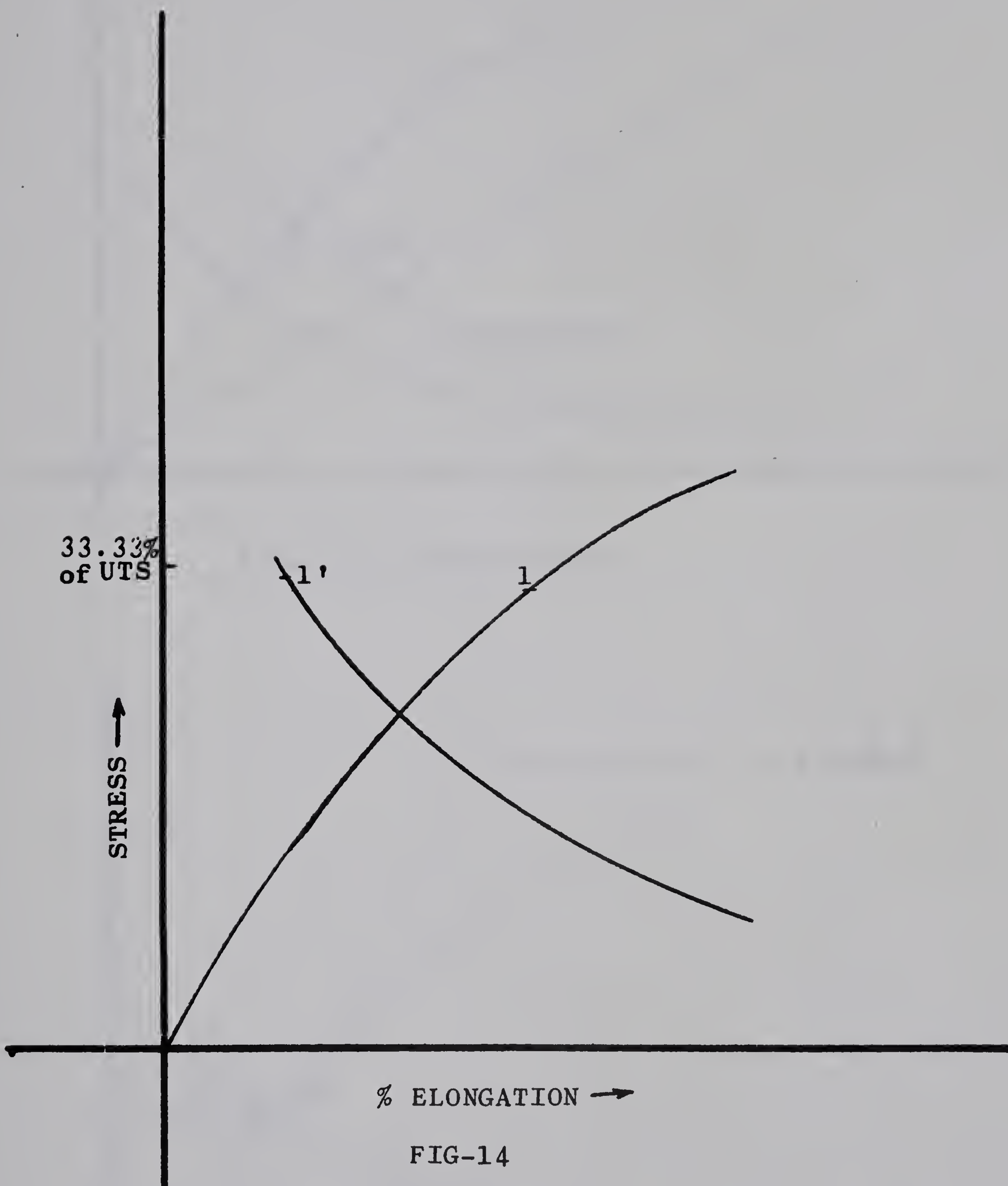


FIG-14

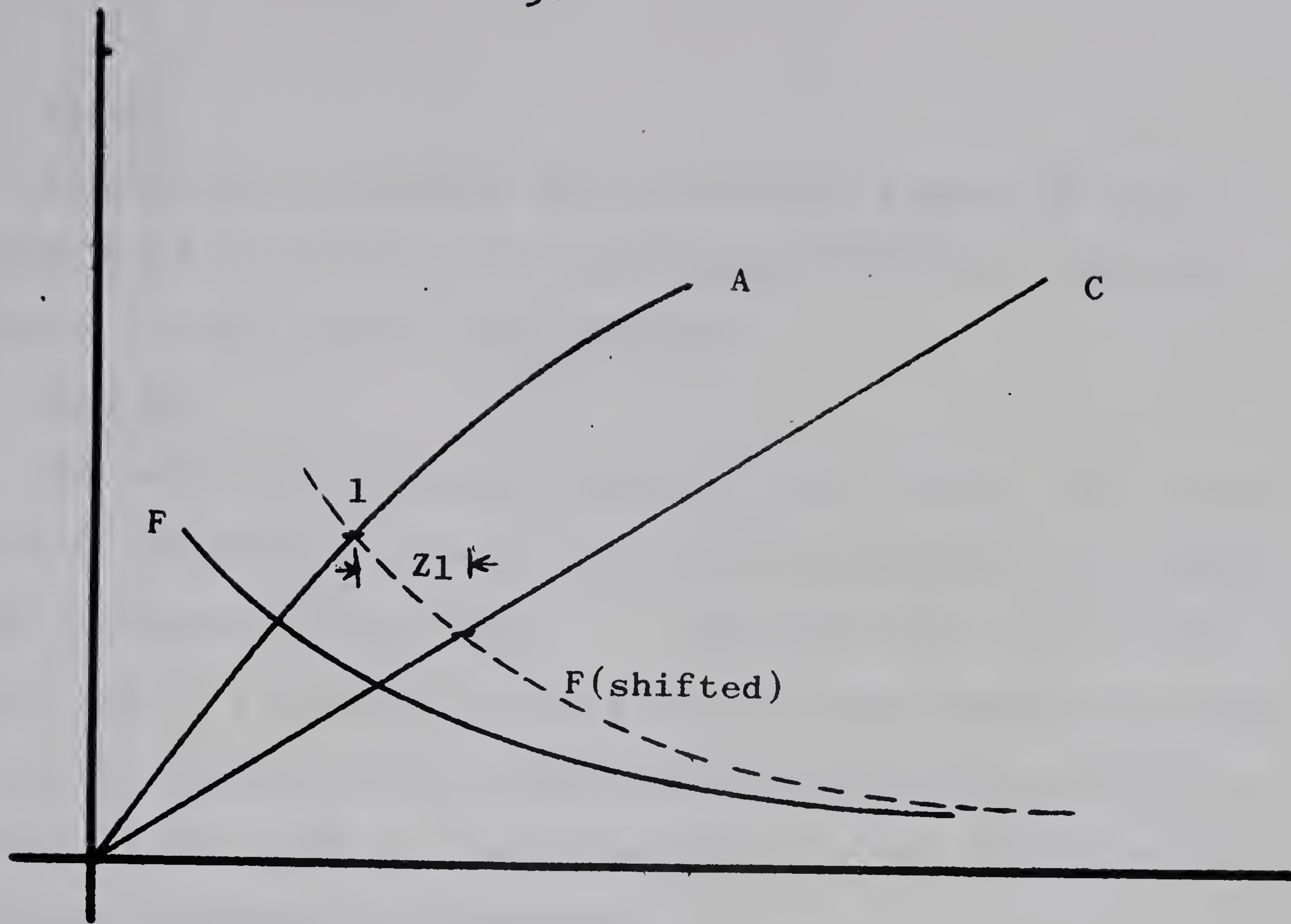


FIG-15 SIX MONTH CREEP

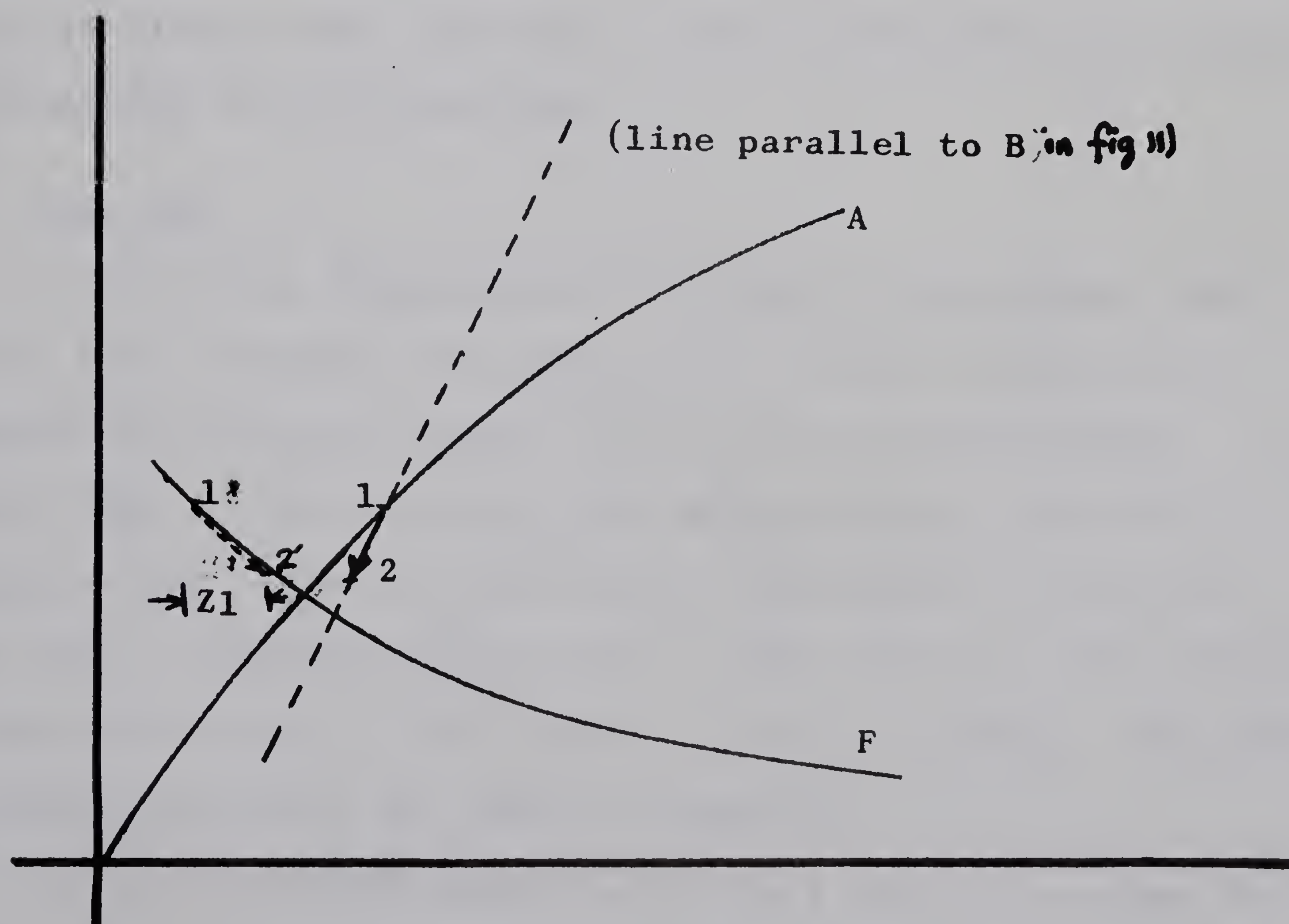


FIG-16 STATE-POINTS AFTER 6 MONTHS CREEP

Step I

Suppose the conductor was as shown in figure-12 and it is tightened on rollers to a tension of $33^{1/3}$% as indicated by state points 1 and 1' (figure-14)

Step II

The conductor undergoes creep for six months. The state-point of the catenary moves downwards along curve-F as elongation increases due to creep, Therefore the creep can be determined by shifting curve-F along the horizontal axis until it reaches point 1 and determining its intersection with the 6 month creep curve C. The intercept Z1 gives creep for six months as indicated in figure-15.

State-point 1' would move to 2' (figure-16) corresponding to the creep Z1. State-point 1 would move to 2 (this movement would be along a line parallel to line B since this corresponds to unloading of the conductor).

Step III

In this step ~~the~~ conductor is loaded to the maximum load. As the load increases the state-point 2 would re-trace its movement and go back towards 1 and if the load increases beyond that it will follow a path along curve A, since the conductor has not been loaded beyond state-point 1 prior to this time. Similarly state-point 2' will follow a path parallel to that of 2 until it hits curve E (loaded catenary). Thus the points will be given by 3 and 3' as shown in figure-17.

Now if the loaded stress (given by 3 and 3') is found to be more than 40% of UTS the procedure has to be repeated with

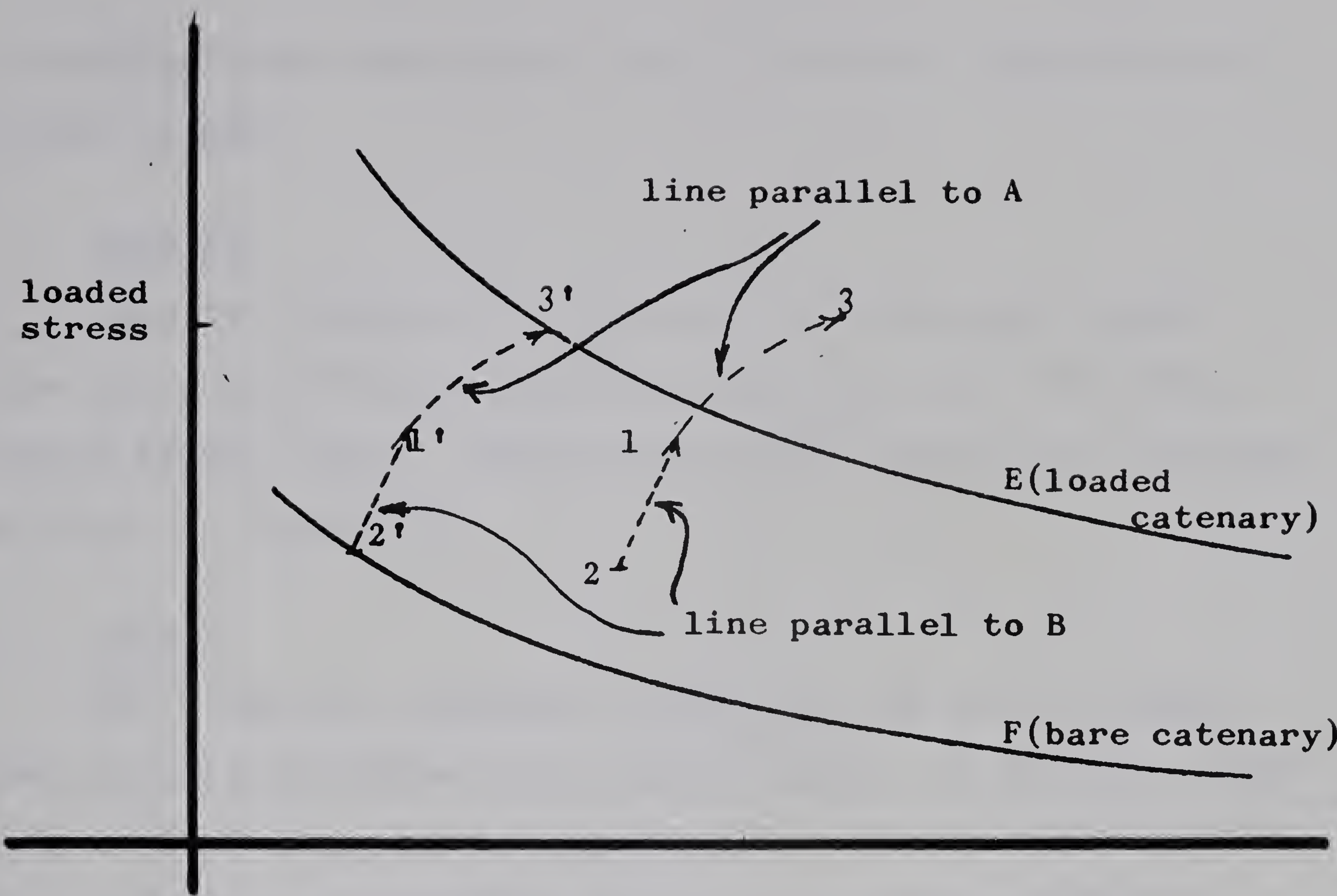

line parallel to A
loaded stress
3'
3
1'
1
E(loaded catenary)
2'
2
line parallel to B
F(bare catenary)

FIG-17

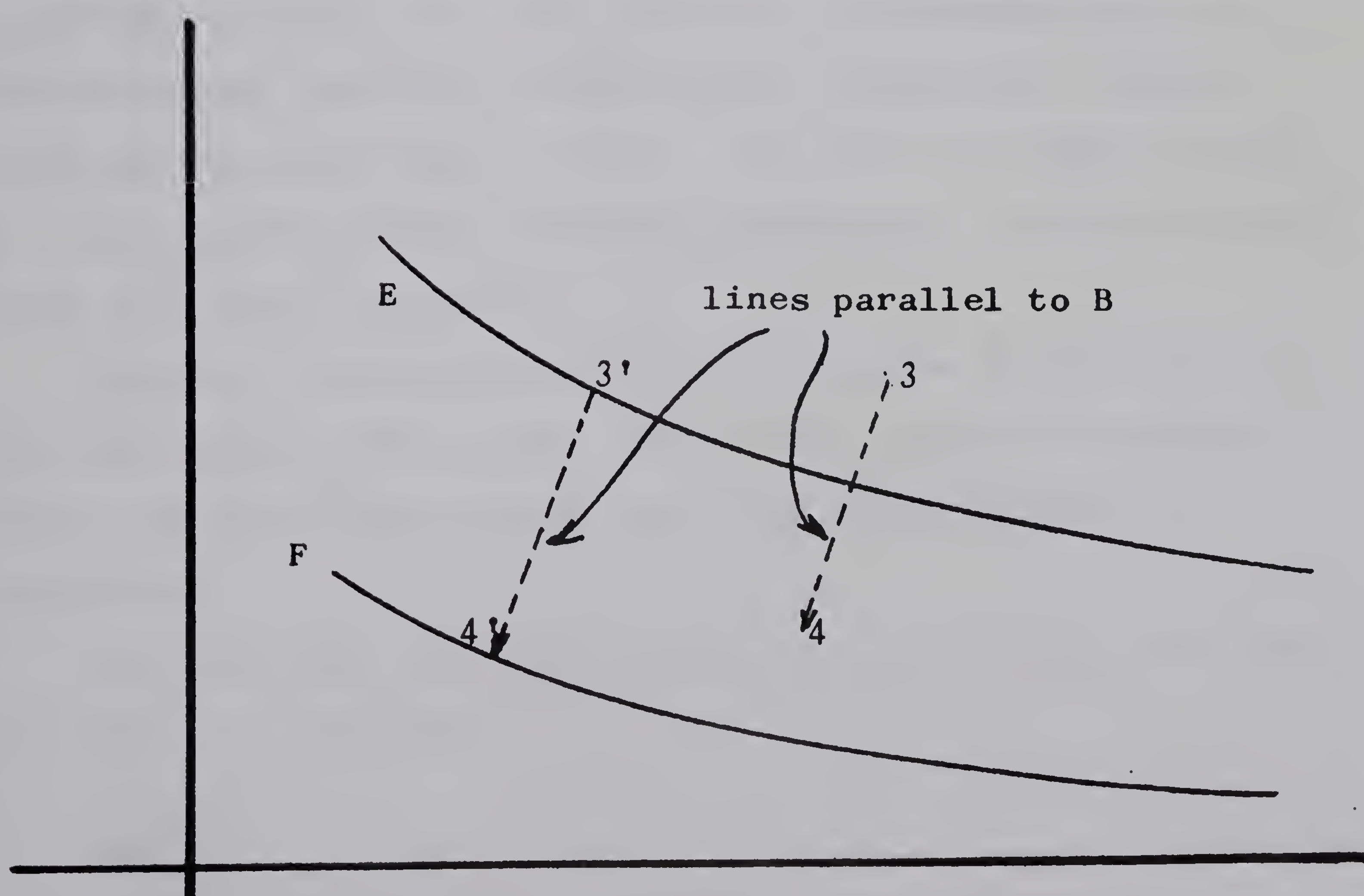

E
lines parallel to B
3'
3
F
4'
4

FIG-18

a starting value lower than $33\frac{1}{3}\%$ of UTS until the loaded condition is met.

Step IV

When the conductor is unloaded the state-point moves from curve E to F following a path parallel to B (the final stress-strain curve). Thus state-points 4 and 4' are obtained as shown in figure-18.

Step V

The conductor undergoes a creep for the next $9\frac{1}{2}$ years. The creep is determined in a manner similar to step II. Curve F is shifted along the horizontal axis until it reaches point 4. Curve-C is also shifted until it passes through point. Curve-D is shifted in a similar manner with a shift equal in magnitude to that of C. The point of intersection between shifted-D and shifted-F is determined (figure-19). Length Z2 gives the creep for $9\frac{1}{2}$ years. Now point 4' moves to point 5' (corresponding to Z2) to give a state-point of the conductor after ten years (figure-20).

Again it is checked whether stress given by point 5' is less than 25% of UTS or not. If not the process is repeated with a smaller initial value until the final tension is satisfied.

At this stage, when the governing condition is determined and Part-A is concluded.

Part B

Suppose the governing condition as described earlier,

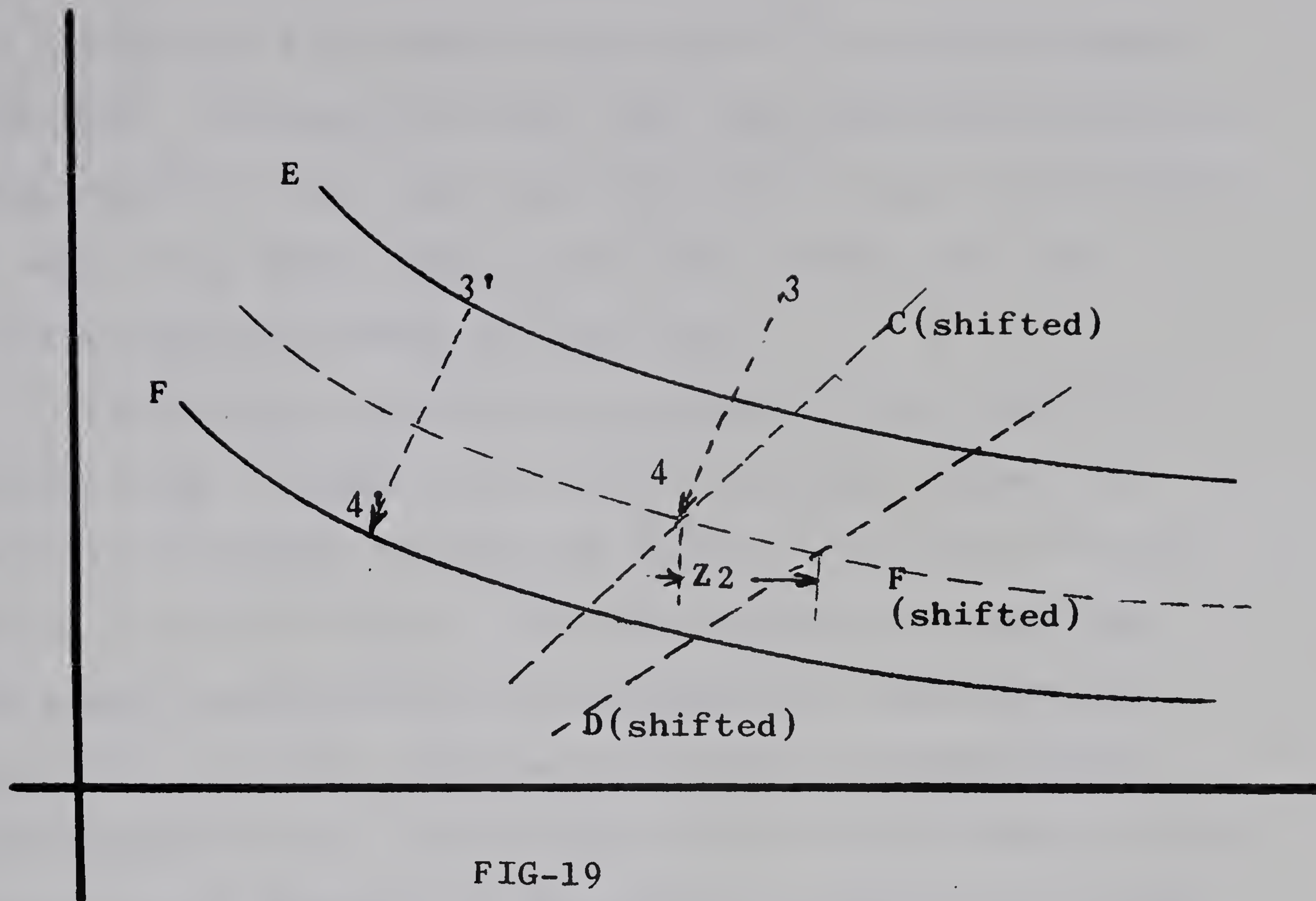


FIG-19

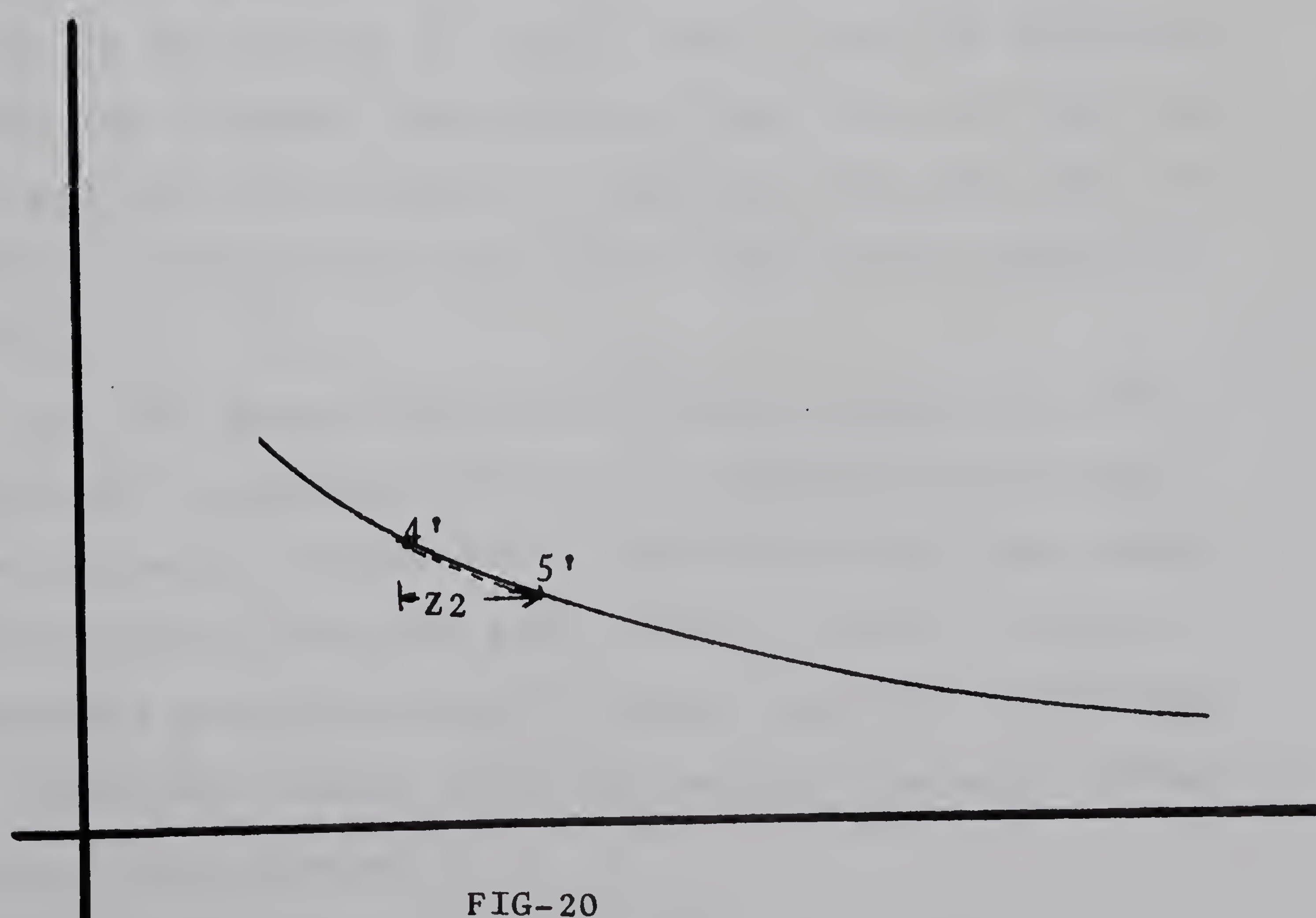


FIG-20

turns out to be: the loaded tension at $0^{o}F$ is not to exceed 40% of UTS. It should be noted that this governing condition is only valid for the span for which the earlier calculations were made. For other spans it is quite likely that the governing condition would be different.

To illustrate the remaining procedure assume that the stringing data is desired for $50^{o}F$. To start assume any reasonable stringing tension for $50^{o}F$ e.g. 33.33% of UTS as shown by O & O' in fig-21. To this state-point apply the temperature transformation to determine the corresponding state-point for $0^{o}F$. Figure-22 shows this transformation. Z_o corresponds to the contraction due to the decrease in temperature and is obtained by utilising the equivalent thermal coefficient for the composite conductor (6). Now since figure-22 is equivalent to figure-14 of step I, a method similar to the earlier one can be used. The only difference is that the succesful completion of step III would mean that all conditions are satisfied. Otherwise one would have to revert to figure-21 to start with a lower value instead of figure-11.

When the proper value for stringing tension for $50^{o}F$ is determined the stringing sag can be obtained from the sag curve (curve-G in figure-11). Completion of all the steps would also give the state point after 10 years. To this a temperature correction can be applied (similar to figure-21) and the sag and tension after ten years at the worst temperature can be determined.

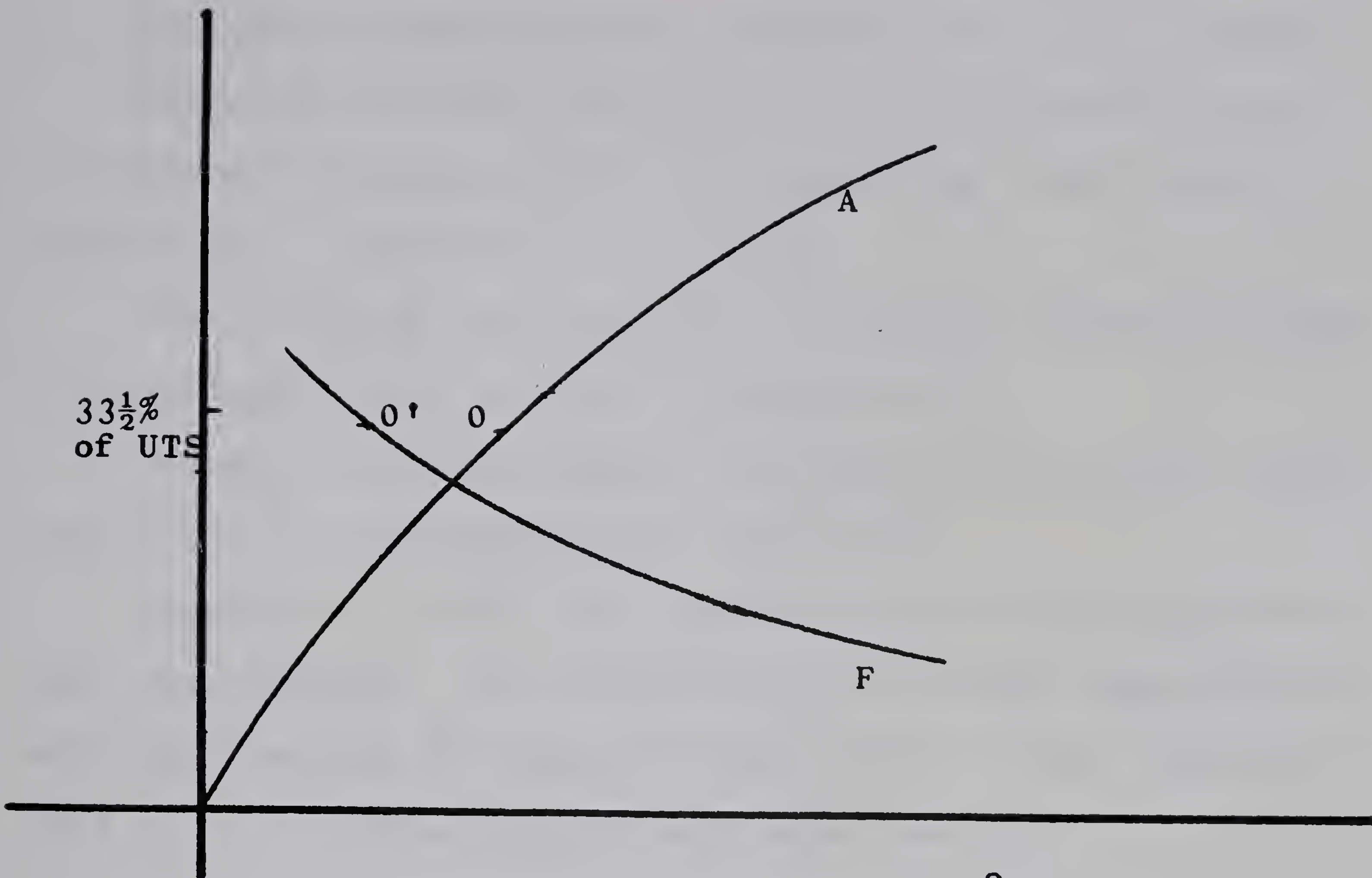


FIG-21 STRINGING STRESS AT 50°F

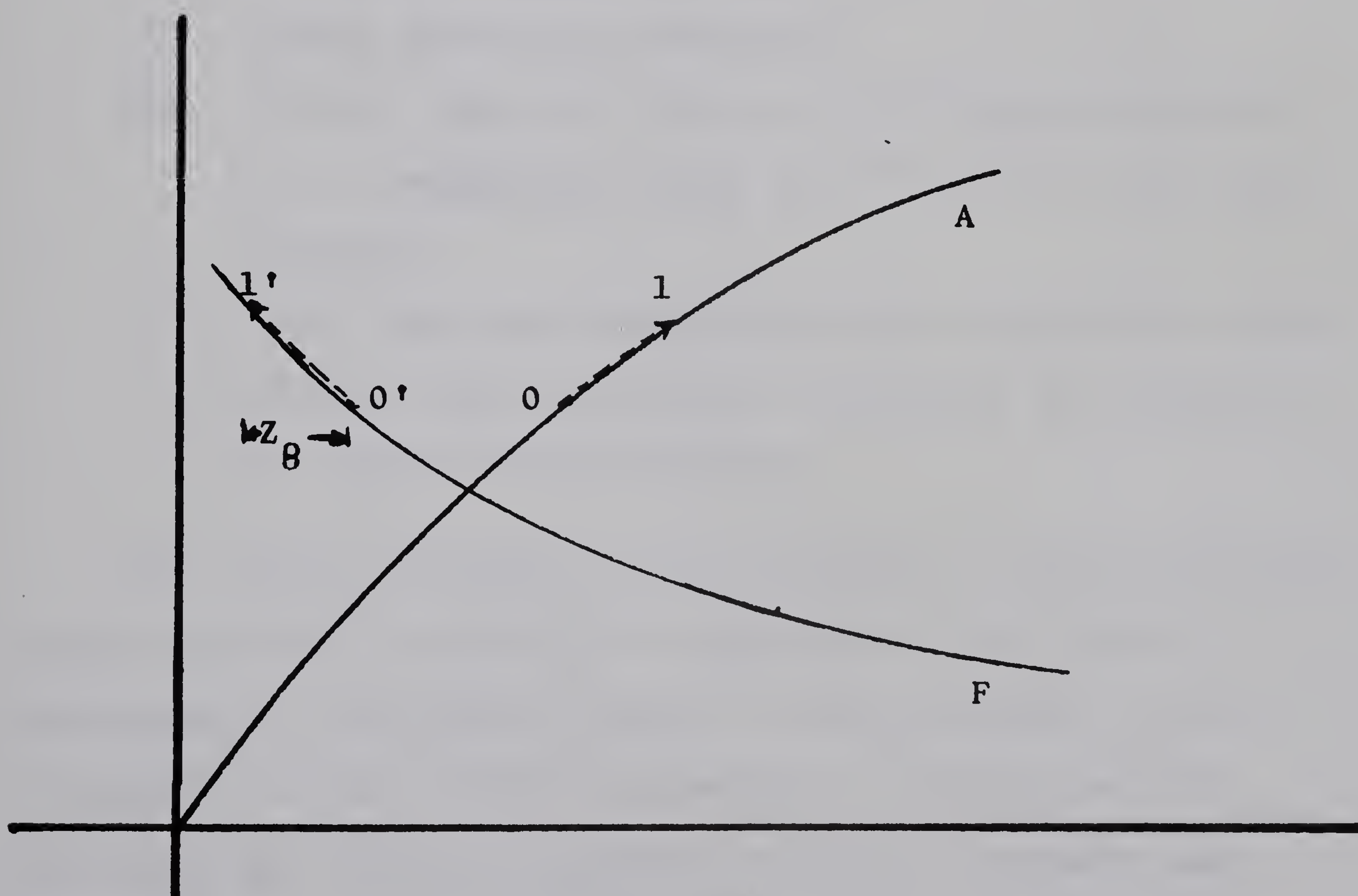


FIG-22 TRANSFORMATION OF FIG-21 TO 0°F

For other temperatures the procedure has to be repeated.

The above-outlined procedure is too time-consuming and involved as stringing tables for a series of spans over a wide range of temperature are needed.

The following sections contain a complete computer program to calculate "ready to use" stringing-charts.

To make it readily usable the program is in metric units and contains explanatory notes throughout.

Appendix-1, at the end, contains result sheets generated with this program. The result sheets are quite comprehensive and tabulate data for spans of 300M, 400M & 500M. Tabulated data gives the following for each span length:

I. Prescribed limiting conditions.

II. Actual governing conditions.

III. Initial sags and tensions for stringing purposes for a temperature range of 15°C-30°C at one degree interval.

IV. Final sags and tensions for same temperature range

V. Maximum expected tension and sag on the conductor for tower design purposes.

The leading authority on this subject is ALCOA with their graphic method. To provide a comparison in the results calculated by the proposed method to that obtained by that of ALCOA's the last sheet in Appendix-1 contains results generated for conditions exactly as given in ALCOA's hand book (5).

Some of the results are tabulated on next page:

Ruling Span = 1000 ft

Tension lb.	Temp. °F	ALCOA's Method	Proposed Method	% change
Initial	60°F	5750	5282	9% lower
Final	60°F	5080	4630	10% lower
Initial	90°F	5250	4740	11% lower
Final	90°F	4750	4289	11% lower

CHAPTER 4

FLOW CHART.

4-1 Introduction.

As explained in chapter-3, the proposed method to obtain stringing-data is very involved and time-consuming. It would not be practicable to do it manually especially if the data is needed for a series of spans over a wide range of temperature. In this chapter a flow-chart is developed for a computer program (Appendix-1) to apply the method and to give the results in a 'ready-to-use' form. Appendix-2 contains some results for a few spans.

4-2 Description of the Flow-Chart:

Box 1: Input Data

In general for ACSR the stress-strain relationship is available in the following form (x-stress; y-strain)

For initial composite:

$$X_i = A + BY_i + CY_i^2 + DY_i^3 \text{ -----------------(5)}$$

$$Y_i = E + FX_i + GX_i^2 + HX_i^3 \text{ -----------------(6)}$$

For final composite:

$$Y_f = JX_f - K \text{ -------------------------(7)}$$

(where K depends upon the maximum value of X_i & Y_i)

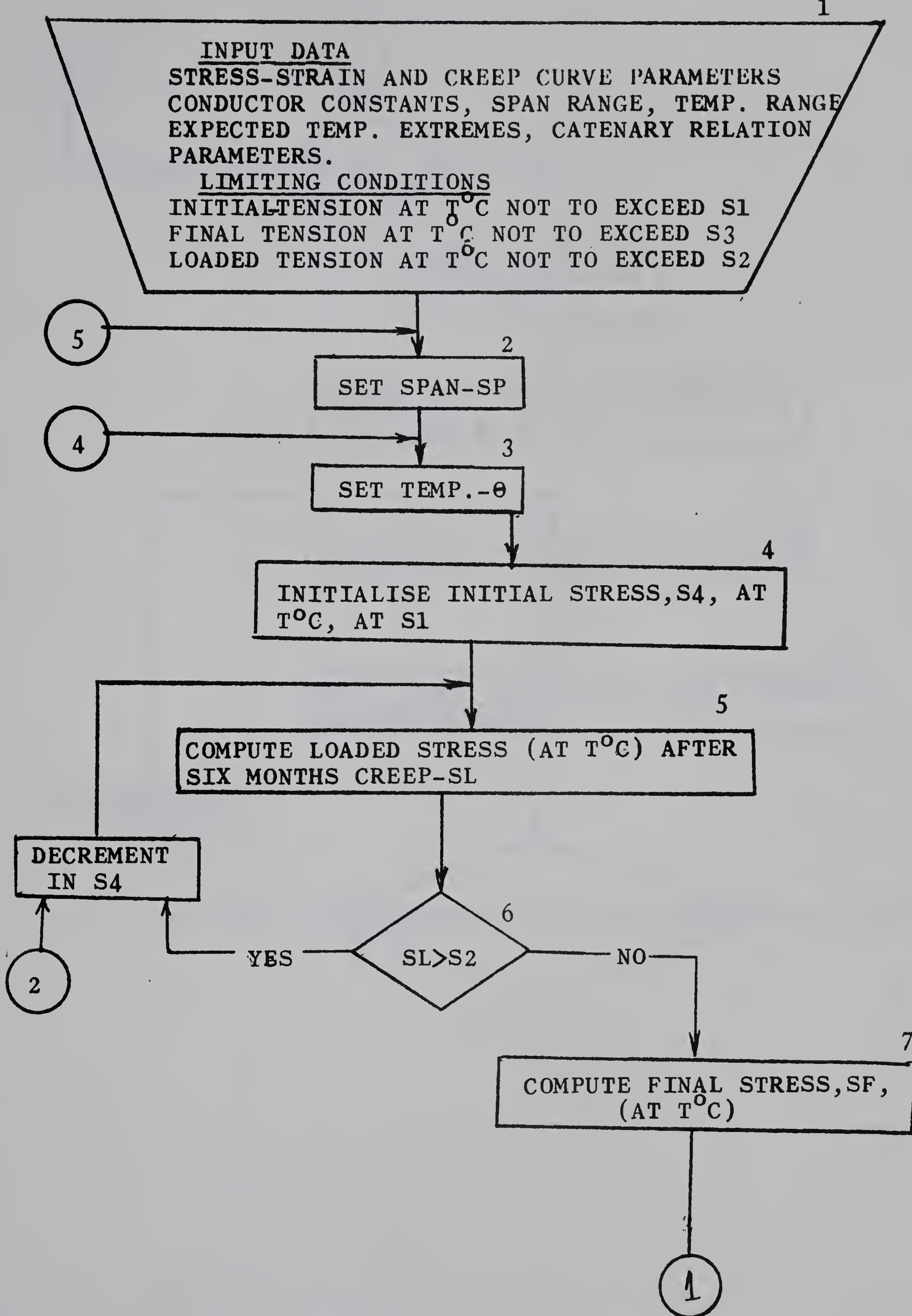
For six months creep:

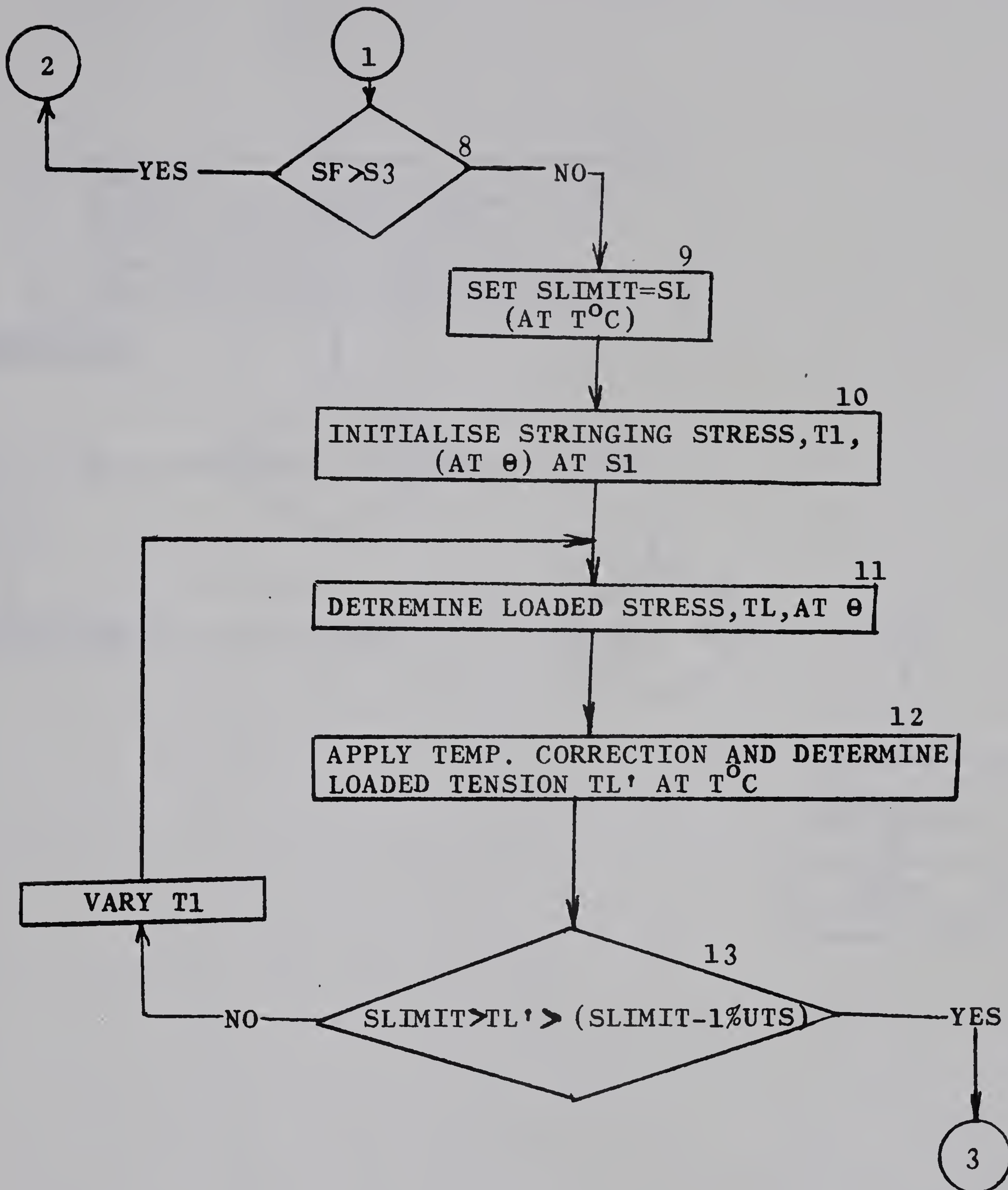
$$Y = MX \text{ ------------------------------(8)}$$

For ten years creep:

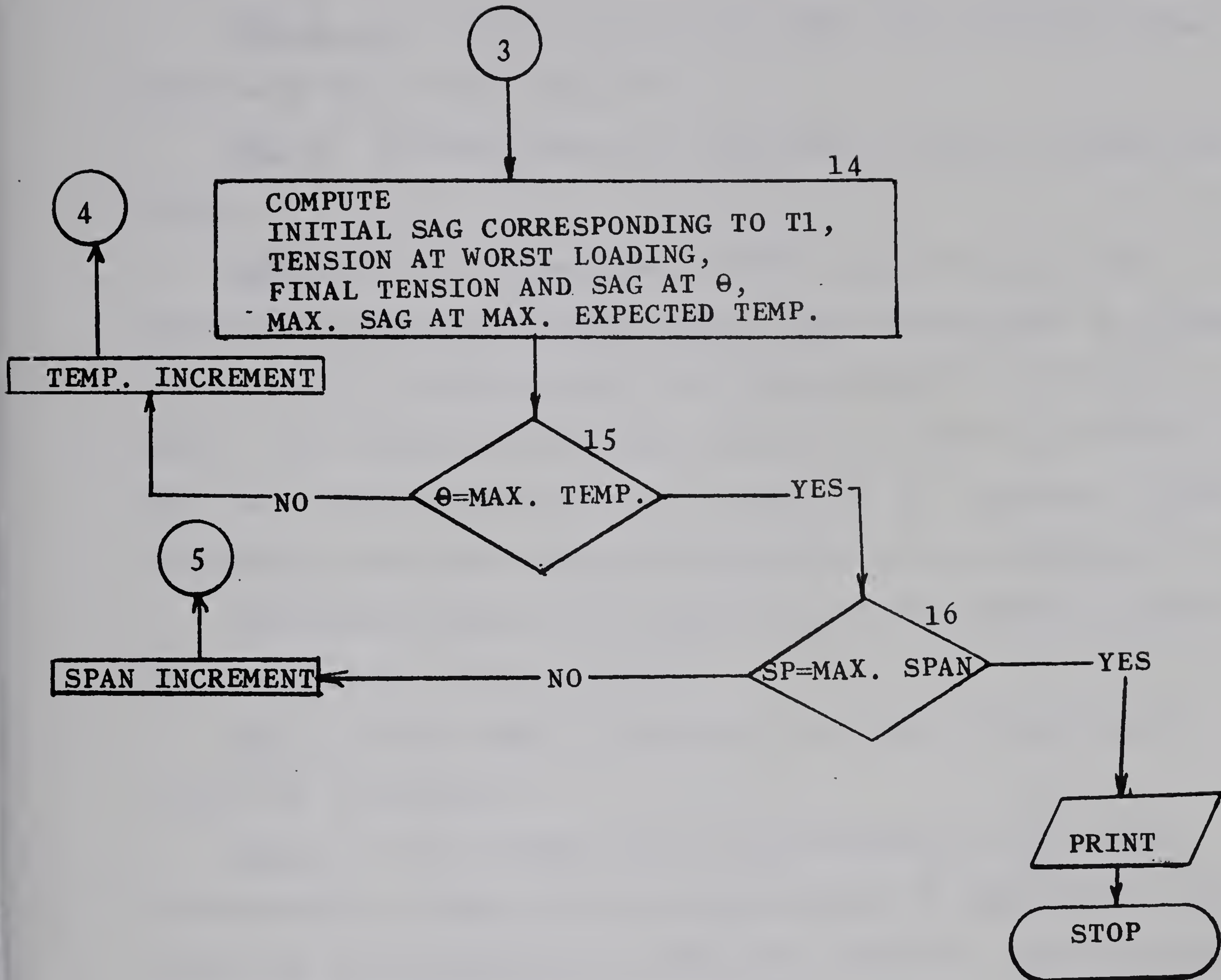
$$Y = NX \text{ ------------------------------(9)}$$

In the above equations A, B, C ----N are constants and subscripts (i) and (f) indicate 'initial' or 'final' value.


1
INPUT DATA
STRESS-STRAIN AND CREEP CURVE PARAMETERS
CONDUCTOR CONSTANTS, SPAN RANGE, TEMP. RANGE
EXPECTED TEMP. EXTREMES, CATENARY RELATION PARAMETERS.
LIMITING CONDITIONS
INITIAL TENSION AT T°C NOT TO EXCEED S1
FINAL TENSION AT T°C NOT TO EXCEED S3
LOADED TENSION AT T°C NOT TO EXCEED S2
5
2
SET SPAN-SP
4
3
SET TEMP.-θ
4
INITIALISE INITIAL STRESS, S4, AT T°C, AT S1
5
COMPUTE LOADED STRESS (AT T°C) AFTER SIX MONTHS CREEP-SL
DECREMENT IN S4
6
YES
SL>S2
NO
2
7
COMPUTE FINAL STRESS, SF, (AT T°C)
1



1
SF > S3
8
YES
2
NO
9
SET SLIMIT=SL
(AT T°C)
10
INITIALISE STRINGING STRESS,T1,
(AT θ) AT S1
11
DETREMINE LOADED STRESS,TL,AT θ
12
APPLY TEMP. CORRECTION AND DETERMINE
LOADED TENSION TL' AT T°C
13
SLIMIT>TL' > (SLIMIT-1%UTS)
NO
VARY T1
YES
3


3
14
COMPUTE
INITIAL SAG CORRESPONDING TO T1,
TENSION AT WORST LOADING,
FINAL TENSION AND SAG AT θ,
MAX. SAG AT MAX. EXPECTED TEMP.
4
TEMP. INCREMENT
15
θ=MAX. TEMP.
NO
YES
5
16
SPAN INCREMENT
NO
SP=MAX. SPAN
YES
PRINT
STOP

BOX 2, 3.: Initial values for span and stringing temperature are set at 'Sp' and 'θ'.

BOX 4: Initial stress at temperature T^oC is initialized at S1.

BOX 5: For a temperature of T^oC loaded tension (SL) is determined after six months creep. This corresponds to figures-15, 16 and 17. For curve-A, B & C equations 6, 7 & 8 are used. For curves E and F the subroutines 'STEL' and 'LOAD' are used (these subroutines are developed for catenary stress-elongation relations and give stress for given elongation)

The Newton-Raphson technique is used to determine points of intersection between curves.

BOX 6: Check made to make sure SL does not exceed S2 (limiting condition).

BOX 7: Final stress (SF) is determined at T^oC. This corresponds to figure-16 in the procedure. In addition to the equations used, equation-9 is used for curve-D. Again Raphson-Newton method is used for iteration.

BOX 8: Check made to see that SF does not exceed S3.

BOX 9: Governing condition 'SLIMIT' is set i.e. current value of SL should not be exceeded at T^oC.

BOX 10: stringing stress at θ is initialized at S1.

BOX 11: In a manner similar to that described for Box-5, loaded tension TL is determined for temperature θ.

BOX 12: Temperature transformation is applied (reduction in elongation calculated by using equivalent coefficient of linear expansion) to determine TL for T^oC - TL'.

BOX 13: Check to make sure that TL' is slightly lower than the governing limiting condition.

BOX 14: Initial sag corresponding to initial tension is determined by using simple catenary relations (subroutine SGEL-developed for catenary relations to give sag for a given elongation). Final sag and tension is determined in a manner similar to that described for BOX 7. Worst tension and maximum sag are determined by applying temperature transformations as described for BOX-12.

BOX 15, 16: Increasing temperature and span to cover the full range for which stringing-tables are desired.

CHAPTER 5

CONCLUSIONS

This thesis provides a means to improve two important aspects of overhead transmission line design. Essentially, this is a step towards optimisation of costs.

Choice of conductor size effects the total cost directly and if a loss of 5% in strength can be tolerated (which seems reasonable) over the life-span of the line then capital costs can be reduced. This approach of using a pre-established risk to select the conductor is similar to loss-of-load techniques used in power-station generation capability design and in the insulation coordination and protection coordination methods.

The new approach is outlined in its basic form. For relatively large projects it would be worthwhile to carry out a more detailed analysis studying the inter-dependencies of the influencing factors. For example a much smaller conductor would be needed if it is seen that in general it is windy during peak hours in summer and still-air conditions during low-load hours.

The new method presented for calculation of installation-data provides an approach as accurate as possible. The extent of accuracy is limited due to uncertainty of some factors e.g. the assumption that the worst conditions would occur after six months of installation.

In the long run this approach may also reduce costs.

The factor of safety chosen by the designer reflects the degree of confidence he has in the method used. Thus the

maximum allowable tension can be chosen to be 60% of UTS (as against 40% of UTS as is generally done) resulting in a saving of a few percent in total costs.

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APPENDIX - I

THE COMPUTER PROGRAM

COMPUTER PROGRAM

```
C     THIS PROGRAM, IN ITS PRESENT FORM, COMPUTES:
C       1. STRINGING TENSION AND STRINGING SAG - FOR
C          CONDUCTOR INSTALLATION PURPOSES
C       2. MAXIMUM SAG AT MAXIMUM TEMPERATURE AFTER TEN
C          YEARS CREEP - FOR TOWER DESIGN PURPOSES
C       3. MAXIMUM TENSION UNDER WORST CONDITIONS - FOR
C          FOR TOWER DESIGN PURPOSES
C
C
C     THE PRESENT FORM DEALS WITH 795 MCM ACSR (54/7)
C     THE VALUES OF VARIOUS DESIGN FACTORS ARE AS GIVEN
C     BELOW. EXPLANATIONS FOLLOW LATER ON TO HELP MAKE
C     MODIFICATIONS FOR OTHER DESIGN CONDITIONS.
      COMMON/A1/W,A,S
      COMMON/A2/P12
      COMMON/A3/WF
      COMMON/A4/P10
      COMMON/A5/P14
      P1=6.85E-4
      P2=2.219E-2
      P3=3.84E-7
      P4=1.621E-11
      P5=-.1687
      P6=51.03
      P7=7.9439
```

```
      P8=-60.95
      P9=.0145
      P10=1./P9
      P11=.0239
      P12=1./P11
      P13=.029
      P14=1./P13
      W=1.525
      A=455.
      ISPMAX=600
      ISPMIN=300
      UTS=12925.
      TMAX=50.
      TMIN=-40.
      ITHIGH=30.
      ITLOW=15.
      WF=2.385
      Y1=52.725E-10
      Y2=202.5E-10
      AL1=.0023
      AL2=.00115
      AR1=403.
      AR2=52.
C     FOLLOWING EXPLANATIONS ARE LISTED TO HELP
C     MAKE SUITABLE MODIFICATIONS FOR DIFFERENT CONDITIONS.
C     W - WEIGHT OF CONDUCTOR (KG/M)
C     WF - LOADING FACTOR ("HEAVY" IN PRESENT CASE AS
```

```
C       DEFINED BY NESC)
C       A - AREA OF CONDUCTOR (SQ. MM.)
C       UTS - ULTIMATE TENSILE STRENGTH OF CONDUCTOR (KG)
C       ISPMAX,ISPMIN - SPAN RANGE FOR WHICH STRINGING DATA
C       IS REQUIRED (M)
C       TMAX,TMIN - MAX & MIN TEMP. EXPECTED (DEG. C)
C       ITHIGH,ITLOW - TEMPERATURE RANGE FOR WHICH STRINGING
C       DATA IS REQUIRED (DEG. C)
C       Y1,Y2 - YNG'S MODULII FOR COM. OF COND. (KG/SQ.MM.)
C       AL1,AL2 - COEFF. OF EXP. FOR COND. COMP. (/DEG.C)
C       AR1,AR2 - SECTIONAL AREAS FOR COND. COMP. (SQ. MM)
C       P1,P2,--ETC - THESE CONSTANTS ARE TAKEN FROM
C       COND. MATERIAL STRESS-STRAIN RELATIONS WHICH ARE
C       USUALLY AVAILABLE IN THE FOLLOWING FORM:
C           ST - STRESS (KG/SQ.MM)
C           EL - UNIT STRAIN IN PERCENTAGE
C         INITIAL COMPOSITE : EL=P1+P2*ST+P3*ST**2+P4*ST**3
C                             ST=P5+P6*EL+P7*EL**2+P8*EL**3
C         FINAL COMPOSITE : EL=P9*ST
C                           ST=P10*EL
C         6 MONTH CREEP : EL=P11*ST
C                         ST=P12**EL
C         10 YEARS CREEP : EL=P13*ST
C                          ST=P14*EL
C           (SINCE IN THIS APPROACH INDIVIDUAL COMPONENTS OF
C           OF THE CONDUCTOR ARE NOT CONSIDERED SEPERATELY
C           AT ANY TIME, THUS WE HAVE NOT BOTHERED TO LIST
```

```
C           THEIR STRESS- STRAIN RELATIONSHIPS)
       DO 100 IS=ISPMIN, ISPMAX,100
      M=0
      S=IS
      WRITE(6,400)S
 400 FORMAT('1',5(/),T30,"RULING SPAN   =",T48,F5.0,T54,
    *'M',/T30,'------------------------')
      WRITE(6,410)
 410 FORMAT('0',T10,'LIMITING CONDITIONS:',T50,
    *'ACTUAL CONDITIONS:')
      WRITE(6,420)
 420 FORMAT(' ',T10,'TENSIONS AT - 18 DEG. C',T50,
    *'TENSIONS AT -18 DEG. C')
      DO 200 ITEMP=ITLOW,ITHIGH, 1
      TEMP=ITEMP
      Z1=UTS/3.
C      Z11,Z22,Z33 CORRESPOND TO THE GIVEN
C      DESIGN CONDITIONS I.E. 33.33%,40% & 25% OF
C      THE UTS ARE LIMITING FIGURES FOR THE INITIAL,
C      LOADED AND FINAL TENSIONS.
      Z11=33.33
      Z2=UTS*.4
      Z22=40.
      Z3=UTS/4.
      Z33=25.
      ALFEQ=(Y1*AL1*AR1+Y2*AL2*AR2)/(Y1*AR1+Y2*AR2)
```

```
      ST1=UTS/(3.*A)
   90 ST=ST1
      CALL ELST (ST,EL)
      EL1=EL
      EL2=P1+P2*ST+P3*ST**2+P4*ST**3
      ELL=EL1-EL2
      AB=.05
      EL3=RAPNEW(AB,ELL)
      CALL STEL(EL3,HRZ, ST3)
      G1=P9*ST3
      G2=EL3-G1
      X0=G2+ST1/P10
      G3=P1+P2*ST1+P3*ST1**2+P4*ST1**3
      G4=X0-G3
      CALL LOAD (WF,P5,P6,P7,P8,P10,G2,G4,ELOAD,X0)
      CALL STEL(ELOAD,HRZ,ST)
      SMAX=ST*WF
      TLOAD=SMAX*A
      IF (TLOAD.LT..4*UTS) GO TO 101
      ST1=ST1-.05
      GO TO 90
```

```
 101 EPI=P9*SMAX
     EP2=EP1-ELOAD
     BC=.01
     EL5=TER1(BC,EP2)
     CALL STEL(EL5,HRZ,ST5)
     EL6=P11**ST5
     EP3=EL6-EL5
     EL10=TER2(BC,EP3)
     CALL STEL(EL10,HRZ,ST10)
     T10=ST10*A
     IF (T10.LT..25*UTS) GO TO 202
     ST1=ST1-.05
     GO TO 90
 202 TI=ST1*A
     M=M+1
     IF (M .GT. 1) GO TO 500
     Z4=(TI/UTS)*100.
     Z5=(TLOAD/UTS)*100.
     Z6=(T10/UTS)*100.
     WRITE(6,430) Z1,Z11,TI,Z4
 430 FORMAT('0',T10,'INITIAL=',F6.0,T25,'KG  =',F5.2,
    *'% OF UTS',T50,'INITIAL='F6.0,T65,'KG   =',F5.2,
    *'% OF UTS')
     WRITE(6,400) Z2,Z22,TLOAD,Z5
 440 FORMAT('0",T10,'LOADED =',F6.0,T25,'KG   =',F5.2,
    *'% OF UTS',T50
    *'LOADED =',F6.0,T65,'KG  =',F5.2,'% OF UTS')
```

```
      WRITE(6,445) Z3,Z33,T10,Z6
445   FORMAT('0',T10,'FINAL  =',F6.0,T25,'KG  =',F5.2,
     *'% OF UTS',
     *T50,"FINAL  =',F6.0,T65,'KG  =',F5.2,'% OF UTS')
500   TLIMIT=TLOAD
      ST2=UTS/(3.*A)
99    ST=ST2
      CALL ELST(ST,EL)
      EL1=EL
      EL2=P1+P2*ST+P3*ST**2+P4*ST**3
      ELL=EL1-EL2
      AB=.05
      EL3=RAPNEW(AB,ELL)
      CALL STEL(EL3,HRZ,ST3)
      G1=P9*ST3
      G2=EL3-G1
      X0=G2+ST1/P10
      G3=P1+P2*ST1+P3*ST1**2+P4*ST1**3
      G4=X0-G3
      CALL LOAD (WF,P5,P6,P7,P8,P10,G2,G4,ELOAD,X0)
      CALL STEL(ELOAD,HRZ,SMAX)
      SMAX=WF*SMAX
```

```
      ETEMP=ALFEQ*(TEMP-TMIN)
      EZERO=ALFEQ*(TEMP+18.)
      EZERO=ELOAD-EZERO
      CALL STEL(EZERO,HRZ,STZERO)
      EWORST=ELOAD-ETEMP
      CALL STEL(EWORST,HRZ,SWORST)
      TWORST=SWORST*WF*A
      TLOAD=STZERO*WF*A
      D=TLIMIT-TLOAD
      IF (ABS(D)  .LT..01*UTS) GO TO 27
      DD=.01*UTS
      IF (D-DD) 3,3,4
    3 ST2=ST2-.5*DD/A
      GO TO 99
    4 ST2=ST2+.5*DD/A
      GO TO 99
   27 DD=.001*UTS
      IF (D.GT. 0.0  .AND. D.LT.DD) GO TO 111
      IF (D-DD)6,6,7
    6 ST2=ST2-.5*DD/A
      GO TO 99
    7 ST2=ST2+.5*DD/A
      GO TO 99
  111 CALL ELST(ST2,EL20)
```

```
      CALL SGEL(EL20,SAG)
      TII=ST2*A
      SGII=SAG
  104 EP1=P9*SMAX
      EP2=EP1-ELOAD
      BC=.01
      EL5=TER1(BC,EP2)
      CALL STEL(EL5,HRZ,ST5)
      EL6=P11*ST5
      EP3=EL6-EL5
      EL10=TER2(BC,EP3)
      EXPND=ALFEQ*(TMAX-TEMP)
      ELMAX=EL10+EXPND
      CALL STEL(ELMAX,H,STEN)
      CALL SGEL(ELMAX,SGMAX)
      CALL STEL(EL10,HRZ,ST10)
      CALL SGEL(EL10,SAG)
      TN10=STEN*A
      TFF=ST10*A
      SGFF=SAG
      IF (M .GT. 1) GO TO 555
      WRITE(6,450)
  450 FORMAT(5(/),T30,'CONDUCTOR INSTALLATION DATA'
     *,/T30,'---------------------------')
      WRITE(6,460)
  460 FORMAT('0',T15,'TEMP',T40,'STRINGING',T60,'FINAL',//
```

```
     *T15,'DEG. C',T32,'TENSION(KG)',T46,'SAG(M)'.
     *T55,'TENSION(KG)',T69,'SAG(M)')
 555 CONTINUE
     WRITE(6,470)TEMP,TII,SGII,TFF,SGFF
 470 FORMAT(T15,F5.1,T34,F6.0,T46,F5.2,T57,F6.0,T69,F5.2)
 200 CONTINUE
     AA=0.
     BB=0.
     GO TO 71
 72  AA=SGMAX
     BB=TWORST
 71  CONTINUE
     IF (SGMAX. .GT. AA) GO TO 72
     IF(TWORST .GT.BB) GO TO 72
     WRITE(6,666)
 666  FORMAT(5(/),T30,'TOWER DESIGN DATA'
     *,/T30,'-----------------')
     CCC=(BB/UTS)*100.
      WRITE(6,667)BB,CCC,AA
 667  FORMAT(2(/),T10,'MAXIMUM EXPECTED TENSION =',F6.0,1X.
     *'KG =' 
     *,F5.2,'% OF UTS'/
     *T10,'MAXIMUM EXPECTED SAG =',F6.2,'M')
 100 CONTINUE
      STOP
      END
C  FUNCTION'DER' CALCULATING THE DERIVATIVE
```

```
C   OF THE CATENARY STRESS CURVE AT VARIOUS
C   POSITIONS ALONG ELONGATION AXIS.
       FUNCTION DER(EL)
       REAL DER
       COMMON/A1/W,A,S
       CALL STEL(EL,HRZ,ST)
       U=ST
       EL=EL+1.E-4
       CALL STEL(EL,HRZ,ST)
       V=ST
       DER=(V-U)*10000.
       RETURN
       END
C   FUNCTION 'RAPNEW'
C   THIS FUNCTION FINDS THE POINT OF INTERSECTION
C   OF THE CATENARY STRESS CURVES AND THE
C   EXPERIMENTAL STRESS- STRAIN CURVES. IT
C   EMPLOYS RAPHSON-NEWTON TECHNIQUES.
       FUNCTION RAPNEW(EL,ELL)
       COMMON/A1/W.A.S
       COMMON/A2/P12
    2  X1=EL
       CALL STEL(EL,HRZ,ST)
       EL=EL-((P12)*(EL-ELL)-ST)/(P12-DER(EL))
       IF (ABS(X1-EL).GT.(5.E-3))  GO TO 2
```

```
      RAPNEW=EL
      RETURN
      END
C   SUBROUTINE 'ELST'
C   THIS SUBROUTINE CALCULATES THE VALUES
C   FOR PERCENTAGE ELONGATION FOR GIVEN VALUES
C   OF STRESS FOR CATENARY STRESS CURVES.
      SUBROUTINE ELST (ST,EL)
      COMMON/A1/W.A.S
      Y1=500.
      Z=W*S
    5 V=2.*Y1
      FCT1=Y1*COSH(Z/V)+Y1-2*A*ST
      DFCT1=1+COSH(Z/V-(Z/V)*SINH(Z/V)
      Y=Y1-FCT1/DFCT1
      IF (ABS(Y1-Y)/Y.LE.(5.E-3))  GO TO 20
      Y1=Y
      GO TO 5
   20 CONTINUE
      IF (Y.LT..1.OR.Y.GT.20000.)  GO TO 22
      EL=((V/W)*SINH(Z/V-S)*100./S
      RETURN
   22 Y1=Y1+500
      GO TO 5
```

```
      END
C  SUBROUTINE 'SGEL'
C  THIS SUBROUTINE CALCULATES SAG FOR
C  GIVEN VALUES OF PERCENTAGE ELONGATION
C  FOR CATENARY RELATIONS
      SUBROUTINE SGEL(EL,SAG)
      COMMON/A1/W,A,S,
      CALL STEL(EL,HRZ,ST)
      H=HRZ*A
      SAG=(H/W)*COSH((S*W)/(2*H)-H/W
      RETURN
      END
C  SUBROUTINE 'STEL'
C  THIS SUBROUTINE CALCULATES STRESS FOR
C  GIVEN VALUES OF PERCENTAGE ELONGATION
C  FOR CATENARY RELATIONS
      SUBROUTINE STEL(EL.HRZ,ST)
      COMMON/A1/W,A,S
      Y1=500.
    5 V=2.*Y1
      Z=W*S
      FCT=((V/W)*SINH(Z/V-S)*100./S-EL
      DFCT=(200./Z)*(SINH(Z/V-(Z/V)*COSH(Z/V)
   10 Y= Y1-FCT/DFCT
      IF ((ABS(Y1-Y)/Y).LE.(1.E-2)) GO TO 20
```

```
      XXX=ABS(Y1-Y)/Y
      Y1=Y
      GO TO 5
   20 CONTINUE
      IF (Y.LT..1.OR.Y.GT.20000.)  GO TO 22
      HRZ=Y/A
      T=Y*COSH((W*S)/(2.*Y))
      ST=(T+Y)/(2.*A)
      RETURN
   22 Y1=Y1+500.
      WRITE(6,57)Y1
      GO TO 5
      END
C  SUBROUTINE 'LOAD'
C  THIS SUBROUTINE CALCULATES THE POINT
C  OF INTERSECTION BETWEEN LOADED CATENARY
C  CURVES AND EXPERIMENTAL STRESS-STRAIN CURVES
      SUBROUTINE LOAD (WF,P5,P6,P7,P8,P10,G2,G4,ELOAD,X0)
      X=.2
    5 X1=X
      CALL STEL(X1,HRZ,ST)
      ST=WF*ST
      CALL ABC (X1,P5,P6,P7,P8,P10,G2,G4,U,X0)
      ST=ST-U
```

```
      X=X-ST/DER1(X,P5,P6,P7,P8,P10,G2,G4,X0)
      IF (ABS(X1-X).GT.5.E-3)  GO TO 5
      ELOAD.=X
      RETURN
      END
C   SUBROUTINE 'ABC'
C   THIS SUBROUTINE GIVES VALUES FOR
C   STESS FOR GIVEN VALUES OF PERCENTAGE
C   ELONGATION FOR EXPERIMENTAL STRESS-STRAIN
C   CURVES.BEFORE GIVING THE VALUE IT DETERMINES
C   THE LOCATION OF THE STATE-POINT I.E.
C   WHETHER IT SHOULD BE ON THE 'INITIAL' OR
C   'FINAL' PORTION OF THE CURVE
      SUBROUTINE ABC (X,P5,P6,P7,P8,P10,G2,G4,U,X0)
      IF (X.GT.SO) GO TO 3
      Y=P10*(X-G2)
      RETURN
 3    U=P5+P6*(X-G4)+P7*(X-G4)**2. +P8*(X-G4)**3
      RETURN
      END
C FUNCTION 'DERL'
C   THIS FUNCTION DETERMINES THE DERIVATIVE
C   OF THE LOADED CATENARY STRESS CURVE
      FUNCTION DER1(EL,P5,P6,P7,P8,P10,G2,G4,X0)
      COMMON/A3/WF
      B=DER(EL)*WF
      CALL ABC(EL,P5,P6,P7,P8,P10,G2,G4,U,X0)
```

```
      C=U
      CALL ABC(EL+1.E-4,P5,P6,P7,P8,P10,G2,G4,U,X0)
      D=U
      F=(D-C)*10000.
      DER1=B-F
      RETURN
      END
C   FUNCTION'TER1'
C   THIS FUNCTION DETERMINES POINT
C   OF INTERSECTION BETWEEN CATENARY STRESS
C   RELATIONS AND EXPERIMENTAL STRESS-STRAIN CURVES.
      FUNCTION TER1(EL,EP2)
      COMMON/A1/W,A,S
      COMMON/A4/P10
    2 X1=EL
      CALL STEL(EL,HRZ,ST)
      EL=EL-((P10)*(EL+EP2)-ST)/(P10-DER(EL))
       IF (ABS(X1-EL).GT.5.E-3)  GO TO 2
      TER1=EL
      RETURN
      END
C   FUNCTION TER2
C   THIS FUNCTION IS SIMILAR TO TER1
C   AND DETERMINES THE POINT OF INTERSECTION
C   BETWEEN CATENARY STRESS RELATIONS
C   AND EXPERIMENTAL STRESS-STRAIN CURVES.
      FUNCTION TER2(EL,EP3)
```

```
      COMMON/A1/W,A,S
      COMMON/A5/P14
    2 X1=EL
      CALL STEL(EL,HRZ,ST)
      EL=EL-((P14)*(EL+EP3)-ST)/(P14-DER(EL))
      IF (ABS(X1-EL).GT.5.E-3) GO TO 2
      TER2=EL
      RETURN
      END
```

APPENDIX II

STRINGING - TABLES

RULING SPAN = 300. M

LIMITING CONDITIONS:
TENSIONS AT -18 DEG. C

INITIAL= 4308. KG =33.33% OF UTS

LOADED = 5170. KG =40.00% OF UTS

FINAL = 3231. KG =25.00% OF UTS

ACTUAL CONDITIONS:
TENSIONS AT -18DEG. C

INITIAL= 3034. KG =23.48% OF UTS

LOADED =5152. KG =39.86% OF UTS

FINAL =1820. KG =14.08% OF UTS

CONDUCTOR INSTALLATION DATA

TEMP	STRINGING		FINAL	
DEG. C	TENSION(KG)	SAG(M)	TENSION(KG)	SAG(M)
15.0	2266.	7.60	2103.	8.19
16.0	2253.	7.64	2094.	8.22
17.0	2240.	7.69	2082.	8.27
18.0	2227.	7.73	2072.	8.31
19.0	2214.	7.78	2060.	8.36
20.0	2195.	7.84	2051.	8.40
21.0	2189.	7.87	2043.	8.43
22.0	2176.	7.91	2033.	8.48
23.0	2156.	7.99	2018.	8.54
24.0	2143.	8.03	2010.	8.57
25.0	2130.	8.08	2004.	8.60
26.0	2124.	8.11	1995.	8.64.
27.0	2105.	8.18	1985.	8.68
28.0	2098.	8.21	1977.	8.72
29.0	2085.	8.26	1967.	8.76
30.0	2072.	8.31	1958.	8.80

TOWER DESIGN DATA

MAXIMUM EXPECTED TENSION = 5833. KG=45.13% OF UTS
MAXIMUM EXPECTED SAG = 9.51M

RULING SPAN = 400. M

LIMITING CONDITIONS: TENSIONS AT -18 DEG. C	ACTUAL CONDITIONS: TENSIONS AT -18 DEG. C
INITIAL= 4308. KG =33.33% OF UTS	INITIAL=2648. KG =20.48% OF UTS
LOADED = 5170. KG =40.00% OF UTS	LOADED =5168. KG =39.98% OF UTS
FINAL = 3231. KG =25.00% OF UTS	FINAL =2297. KG =17.77% OF UTS

CONDUCTOR INSTALLATION DATA

TEMP	STRINGING		FINAL	
DEG. C	TENSION(KG)	SAG(M)	TENSION(KG)	SAG(M)
15.0	2298.	13.35	2154.	14.25
16.0	2286.	13.42	2145.	14.32
17.0	2279.	13.46	2140.	14.35
18.0	2273.	13.50	2135.	14.38
19.0	2266.	13.54	2129.	14.42
20.0	2253.	13.62	2121.	14.48
21.0	2247.	13.66	2115.	14.52
22.0	2240.	13.70	2111.	14.55
23.0	2234.	13.74	2105.	14.59
24.0	2221.	13.82	2095.	14.66
25.0	2214.	13.86	2091.	14.69
26.0	2208.	13.90	2086.	14.73
27.0	2202.	13.94	2081.	14.77
28.0	2195.	13.98	2076.	14.80
29.0	2189.	14.03	2071.	14.84
30.0	2176.	14.11	2061.	14.91

TOWER DESIGN DATA

MAXIMUM EXPECTED TENSION = 5511. KG -42.64% OF UTS
MAXIMUM EXPECTED SAG = 15.67M

RULING SPAN - 500. M

LIMITING CONDITIONS: TENSIONS AT -18 DEG. C	ACTUAL CONDITIONS: TENSIONS AT -18 DEG. C
INITIAL= 4308. KG =33.33% OF UTS	INITIAL= 2443. KG =18.90% OF UTS
LOADED = 5170. KG =40.00% OF UTS	LOADED = 5140. KG =39.77% OF UTS
FINAL = 3231. KG =25.00% OF UTS	FINAL = 2261. KG =17.49% OF UTS

CONDUCTOR INSTALLATION DATA

TEMP	STRINGING		FINAL	
DEG. C	TENSION(KG)	SAG(M)	TENSION (KG)	SAG(M)
15.0	2253.	21.35	2149.	22.41
16.0	2253.	21.35	2149.	22141
17.0	2247.	21.41	2145.	22.45
18.0	2240.	21.48	2139.	22.52
19.0	2234..	21.54	2135.	22.57
20.0	2234.	21.54	2135.	22.57
21.0	2227.	21.61	2129.	22.62
22.0	2221.	21.67	2124.	22.68
23.0	2214.	21.74	2119.	22.74
24.0	2214.	21.74	2119.	22.74
25.0	2208.	21.80	2114.	22.79
26.0	2202.	21.87	2109.	22.85
27.0	2195.	21.93	2103.	22.92
28.0	2195.	21.93	2103.	22.92
29.0	2189,	22.00	2098.	22.97
30.0	2182.	22.06	2192.	23.04

TOWER DESIGN DATA

MAXIMUM EXPECTED TENSION = 5340. KG=41.31% OF UTS
MAXIMUM EXPECTED SAG = 23.81M

RULING SPAN = 1000. FT

LIMITING CONDITIONS: TENSIONS AT 0 DEG. F	GOVERNING CONDITIONS: TENSIONS AT 0 DEG. F
INITIAL= 9500. LB =33.33% OF UTS	INITIAL= 7278. LB =25.54% OF UTS
LOADED=11400. LB = 40.00% OF UTS	LOADED=11382. LB =39.94% OF UTS
FINAL = 7125. LB =25.00% OF UTS	FINAL = 4020. LB =14.10% OF UTS

STRINGING DATA

TEMP	STRINGING		FINAL	
DEG. F	TENSION	SAG	TENSION	SAG
60.0	5280.	24.31	4630.	27.76
70.0	5068.	25.34	4500.	28.57
80.0	4897.	26.23	4392.	29.27
90.0	4740.	27.10	4289.	29.98
100.0	4598.	27.95	4193.	30.68

TOWER DESIGN DATA

MAXIMUM EXPECTED TENSION =12903. LB
MAXIMUM EXPECTED SAG = 31.97FT